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INTRODUCTION

1.1 BACKGROUND TO THE STUDY

The adequate supply of world energy requirements is a global concern. Although there is much investment and ongoing research in wind, solar and wave energy sources, large-scale viability is currently limited. According to the Oxford International Biomedical Centre (OIBC) report, fossil fuels still provide 80% of global energy requirements, even though such fuels pose serious threats to the environment (OIBC Report, 2008:4). As stated by Holton (2005), a spin-off result of the aforementioned statistic is that the question of whether governments should encourage the construction of new nuclear power plants is no longer beyond consideration in developed countries, such as Australia, the United Kingdom and the United States. However, for other developed countries, such as France and Japan, and for countries with fast-growing economies, such as China and India, nuclear energy is and has remained a central component of energy policies (Holton, 2005).

Part of this renewed interest in nuclear technology is the development of packed pebble bed gas-cooled reactors. Factors that drive these interests are safety, extended scope of application and higher efficiencies both on the power conversion system and fuel conversion ratio. High temperature helium-cooled reactors date back as far as 1947 when first proposed by Farrington Daniels. However, the first CO_2 gas-cooled power reactor began operation at Calder Hall in England in 1956, producing 40 MW of electricity. To date, development of the high temperature gas-cooled reactor termed the Pebble Bed Modular Reactor (PBMR) forms part of the generation-four reactor technology developments and is of interest for the current study.

Inherent safety is claimed for such Pebble Bed Reactors (PBR) as a result of its design, materials used, fuel type and physics involved. With the PBMR, the basic danger of a "core melt down" accident is overcome by the lower power density of the core (30 times lower than a Pressurised Water Reactor (PWR)), which is typical for any graphite-moderated reactor, due to the thermal storage characteristics of pebble fuel (600 times higher than PWR fuel) and due to its design deterministically excluded. The bed consists of a large number of randomly packed pebbles/spheres each made up of many triso-coated fuel particles. This is illustrated in Figure 1.1. Helium, which is chemically inert, transfers heat from the core by convection to either the power-generating gas turbines or process heat applications (PBMR, 2009).

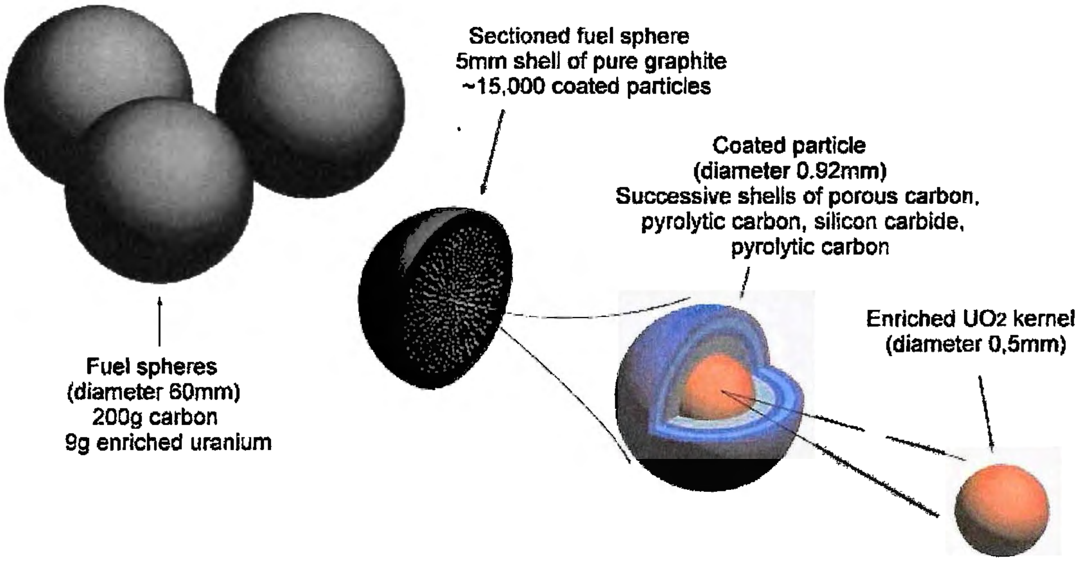

Figure 1.1: Pebble Bed Modular Reactor triso-coated fuel particles (PBMR, 2009)

A proper understanding of the mechanisms of heat transfer, flow and pressure drop through a packed bed of spheres is of importance in the design of high temperature PBRs. In this study, correlations describing the effective thermal conductivity through an annular core PBR are examined. Total effective thermal conductivity of a packed bed is a term defined as representing the heat transfer through a packed bed of spheres in the radial direction. This term is the summation of three components (Bauer, 1990:2.8.1–1), i.e. the fluid effective thermal conductivity due to the turbulent mixing of the fluid flowing through the voids of the packing in parallel with the wall, the effective thermal conductivity due to the movement (stirring) of solid spheres and the effective thermal conductivity due to thermal conduction and thermal radiation in a stagnant fluid environment. In this study, the latter is investigated.

This topic is of great importance because the phenomenon forms such an intricate part of the self-acting decay heat removal chain, which is directly related to the PBR safety case. Decay heat is defined as the remaining heat in a PBR in severe upset conditions. This heat can either be removed by active cooling measures or by passive cooling in the radial direction.

Standard correlations used by the general thermal fluid community for PBRs are investigated, with particular attention to the range of applicability of the correlations when simulating the effective thermal conductivity in the near-wall regions. Despite decades of experimental and theoretical work, predicting the effective thermal conductivity in a randomly packed bed, continues to be of great interest in the chemical and nuclear industries. The difficulty lies in the effective thermal conductivity being a phenomenological characterisation of an arrangement of solid-fluid/gas mediums rather than a thermo-physical property. Consequently, much of the research on the simulation of the effective thermal conductivity has been conducted in the bulk region of a packed bed, where the porous structure is mostly uniform and the phenomenological characterisation of the solid-fluid/gas mediums becomes relatively simple. Various studies have demonstrated that the porous structure in a PBR varies significantly near the wall, as the geometry of the packing is disrupted in this region.

Finally, a new model termed the Multi-sphere Unit Cell is proposed that describes the effective thermal conductivity in the bulk and near-wall regions of a randomly packed bed. This is important as both the bulk and near-wall regions contribute to decay heat removal in severe upset conditions. Conclusions are derived by comparing simulation results with measurements from five distinct experimental test facilities, including the High Temperature Test Unit (HTTU) as described by Rousseau and Van Staden (2008:3060).

1.2 RESEARCH PROBLEM STATEMENT

The correlations most commonly employed to characterise the effective thermal conductivity in the nuclear environment are those developed by Schlünder and co-workers (Zehner & Schlünder, 1970:933; Zehner & Schlünder, 1972:1303; Bauer & Schlünder, 1978:189) as well as Breitbach & Barthels (1980:392). These correlations predict the effective thermal conductivity by considering a cylindrical unit cell that contains two half spheres in contact with deformable shapes. There are no clear guidelines as to the accuracy and validity of the Zehner, Bauer and Schlünder (ZBS) equation. However, the experimental data considered by Tsotsas & Martin (1987:19) was found to lie in a ±30% band around the model predictions.

An explanation provided by Cheng *et al.* (1999:4199) is that a geometrical unit cell is too simple to represent the porous structure of a randomly packed bed. Agreement is obtained with a high degree of empiricism, as highlighted by the number of parameters that have to be determined by means of curve-fitting to experimental data. According to the Niessen & Ball (2000:321), using the ZBS unit cell to model the effective thermal conductivity is only viable for the bulk region of a pebble bed and not for the boundary regions near the inner and outer reflector interfaces. The pebble-to-reflector heat transfer is important for two reasons. Firstly, the reactivity of the control rods housed in the reflectors is highly temperature dependent. Secondly, the pebble-to-reflector interface is on the critical path for decay heat removal during accident conditions, as described by Van der Merwe *et al.* (2006:1).

An experimental test facility, termed the SANA-I experiment, was constructed at Jülich nuclear research centre Germany to investigate the effective thermal conductivity for high temperature PBRs (Stöcker, 1998:24; Niessen & Ball, 2000:296). Experiments were conducted at gas pressures close to atmospheric conditions resulting in natural convection driven flows to be present. This limited the use of the data for validation of the effective thermal conductivity calculations. In addition, near-wall effects could not clearly be extracted from the temperature measurements, owing to the limited number of thermocouples used in the radial direction.

One of the experimental test results of the SANA-I experimental facility saturated with helium, the 35 kW long heater test is displayed in Figure 1.2. Niessen & Ball (2000:301) proposed a summation of three correlations (denoted as IAEA ZS total) to simulate the effective thermal conductivity in a stagnant gas environment, i.e. the Zehner & Schlünder (1970:933) correlation for point conduction, the Kaviany (1991:127) correlation for conduction through the contact area, and the correlation developed by Breitbach & Barthels (1980:392) for thermal radiation.

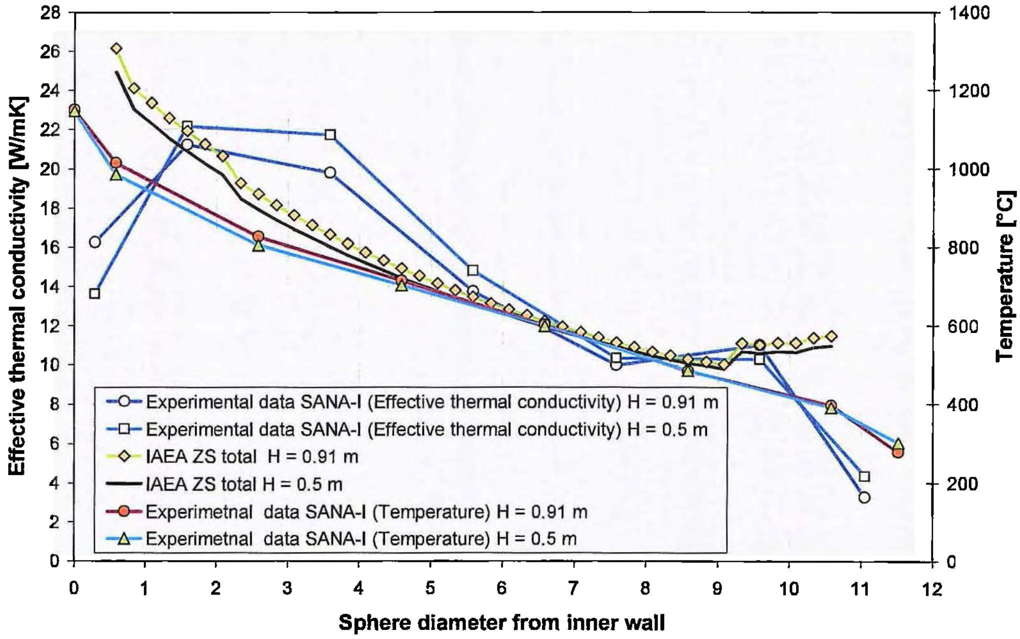

Figure 1.2: SANA-I experimental data 35 kW long heater with helium as the interstitial gas (see Table C.11)

It is evident from the aforementioned analysis that the IAEA ZS total correlation breaks down when simulating heat transfer for the interface between the pebble bed and the inner and outer reflectors of the annular core. Correction factors of 0.6 at the heating element (inner reflector) and 0.5 at the outer reflector interface were proposed by Niessen & Ball (2000:321). These correction factors are then multiplied with the effective thermal conductivity results of the IAEA ZS total correlation in the region half a sphere diameter from the reflector interface.

It is clear from the empirical correction factors that there is no precise understanding of the heat transfer between the pebble and reflector interface. Also owing to the number of thermocouples in the radial direction, it cannot be seen whether the reflector wall has an effect on effective thermal conductivity further into the packed bed (Figure 1.2).

This let to the design and construction of the High Temperature Test Unit (HTTU) at Potchefstroom, North-West University, South Africa. The experimental data from the HTTU is much more useful for various reasons. One of the advantages of the HTTU is its ability to generate detailed temperature profiles at near-vacuum conditions, $P_g = 10kPa(abs)$, up to 1200°C. This advantage results in improved accuracy of the extraction of the radial effective thermal conductivity in order to determine the near-wall impact on the effective thermal conductivity.

1.3 METHODOLOGY

Effective thermal conductivity correlations have been developed for a wide variety of applications. However, this study focuses on two equally important components. Firstly, the study presents a fundamental understanding of the porous structure in an annular randomly packed bed consisting of uniform-sized spheres. It identifies the shortcomings in characterising porous structure with parameters obtained in open literature and seeks new methods to characterise the porous structure.

Secondly, the study presents a fundamental understanding of the various heat transfer mechanisms contributing to the effective thermal conductivity in PBRs. It presents the range of applicability and shortcomings of the correlations found in open literature to simulate the effective thermal conductivity in the bulk, as well as the near-wall regions; and develop new correlations to simulate the effective thermal conductivity in the bulk, as well as in the near-wall region.

For this study, it is assumed that the gas conditions throughout the packed bed are stagnant and therefore no natural convection driven flows are taken into account. It is also assumed that the gas temperature and the measured temperature in the middle of the solid sphere is the same as for the case of the HTTU. This is a valid assumption owing to the high thermal conductivity of the HTTU graphite spheres. This study also assumes no movement of spheres and therefore only evaluates heat transfer for a fixed packed bed.

1.4 CONTRIBUTIONS OF THIS STUDY

The study aims to demonstrate comprehensively the critical importance of a fundamental understanding of the porous structure prior to attempting any heat transfer analysis. Six different methods to characterise the porous structure in randomly packed and structured packed beds were investigated. One of these is a newly defined method to characterise the porous structure with the contact angle between adjacent spheres. This method shows promising results when used in association with the heat transfer analysis.

Another contribution of this study is the development of the Multi-sphere Unit Cell Model for the bulk and the near-wall region. This model attempts to characterise the effective thermal conductivity with the least amount of empiricism. The Multi-sphere Unit Cell Model is the summation of two components: thermal conductivity and thermal radiativity.

Two thermal resistance networks were subsequently developed to characterise the contact areas with rough (Rough Contact Network) or smooth (Hertzian Contact Network) surfaces in simulating the thermal conduction component.

In addition, a new method is introduced to address the decrease in thermal conductivity in a gas with a decrease in system pressure. This method uses a newly defined mean-free path radius characterising the boundaries of the Smoluchowski effect where it is compared with experimental data and found to show promising results.

Furthermore, thermal radiation is also addressed by two newly developed sub-components: short-range thermal radiation and long-range thermal radiation. *Short-range thermal radiation* is defined as the radiation between spheres in contact, and *long-range thermal radiation* is defined as the thermal radiation through the voids between spheres not in contact.

The Multi-sphere Unit Cell is developed in such a way that when an improved model of a certain thermal resistance or other quantity is developed in the future, it can be implemented with relative ease. It is demonstrated that the solid region of the sphere can be divided into multiple thermal resistances to accommodate a pebble consisting of a fuel matrix.

Lastly, the porous structure can be simulated quite accurately using the Discrete Element Method (DEM) as shown by Du Toit (2008:3073). Using a numerically generated packed bed in combination with the Multi-sphere Unit Cell, a PBR can be simulated without any empiricism of the porous structure under consideration. This enables the simulation to calculate the temperature in the centre of each sphere emphasising regions of concern with various input parameters, such as gas pressures, contact area pressures due to the weight of the packing, and heat fluxes.

1.5 CHAPTER OUTLINE

Following this introduction chapter, Chapter 2 presents an overall background on the open literature regarding packing structures. Furthermore, several aspects regarding the wall and thickness effects are investigated in terms of cylindrical and annular packed beds. Chapter 3 discusses the literature regarding heat transport through mono-sized randomly packed spheres. Chapter 4 examines the HTTU experimental test facility and the extraction of the effective thermal conductivity from the measurements. It also briefly mentions the use of other experimental data sets to validate the Multi-sphere Unit Cell Model. Chapter 5 demonstrates the development of the Multi-sphere Unit Cell Model capable of simulating the effective thermal conductivity in the bulk region and wall region of a packed bed. Chapter 6 discusses the comparison of the Multi-sphere Unit Cell Model with various experimental data sets. Lastly, Chapter 7 summarises the study and provides recommendations for further work.