The system CFD approach applied to a pebble bed reactor core

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1 Nomenclature

β_{max}	Surface node maximum length fraction
B_i	Biot number
h	transfer coefficient
k	conductivity
L	characteristic length
R_i	pebble bed inner radius
R_o	pebble bed outer radius
T	temperature

2 Abstract

The system CFD code Flownex is used to simulate the transient behaviour of complete thermal-fluid systems such as the Pebble Bed Modular Reactor. In the context of this system simulation, the complexities in modelling the reactor heat transfer is discussed, as well as appropriate methods of dealing with it. The versatility of the system CFD approach is illustrated with three possible topologies for the pebble bed reactor core model. It is shown that the current pebble bed network topology compares very well to other possible network topologies, while having the advantage of predicting the maximum fuel temperature.

3 Keywords

Thermal-fluid, system CFD, PBMR, Flownex, thermal conduction network, topology, gas cooled reactor, core modelling.

4 Biographical notes

Gideon Greyvenstein

Gideon Greyvenstein is professor in mechanical engineering at Potchefstroom University for Christian Higher Education. Until recently he was dean of the Faculty of Engineering at Potchefstroom University. Prior to joining the University he worked for seven years in industry and has extensive experience as a consulting engineer.

He is registered as a Professional Engineer with the Engineering Council of South Africa (ECSA) and serves on the following ECSA committees: the Education Advisory Committee and the University Accreditation Committee. He also serves on the academic council, as country representative for South Africa, of the newly inaugurated World Nuclear University.

Prof. Greyvenstein has more than 25 years experience in the design of thermal-fluid equipment for industry. He pioneered the development of a range of industrial heat pumps and has also pioneered the development of a number of thermal-fluid simulation packages. One of these is a thermal-fluid network code that is used for the detail design of the complete power conversion cycle of the new Pebble Bed Modular Reactor. Prof. Greyvenstein also serves on the board of two industrial companies.

Herman van Antwerpen

Herman van Antwerpen received his Masters in Mechanical Engineering at Potchefstroom University on the subject of water turbines for pressure relief and energy recovery in mine cooling water networks. Currently, he is a full-time PhD student at Potchefstroom University. The subject of his study is heat transfer modelling in pebble bed high-temperature gas cooled reactors.

Pieter Rousseau

Dr Rousseau is professor in Mechanical Engineering and Director of Energy Systems Research at Potchefstroom University. He has published more than 50 papers in international journals and conference proceedings. He also co-authored a chapter on heat pump design and optimisation in a textbook and currently serves on the editorial board of the international journal 'Nuclear Engineering and Design'. He is a registered professional engineer with practical experience ranging from computational fluid dynamics to the design of thermal fluid systems including an energy efficiency award-winning heat pump system and the first operating model of the three-shaft, closed-loop Pebble Bed Modular Reactor (PBMR) gas

turbine power plant. He is also a member of the Flownex system CFD simulation software development team.

5 Introduction

The Pebble Bed Modular Reactor (PBMR) is a high temperature gas cooled nuclear power plant currently being developed by the South African utility ESKOM. It features a direct, three-shaft Brayton cycle with helium as working fluid. The cycle-layout is shown schematically in Figure 1. The complete power cycle, including the reactor is modelled with the dynamic system Computational Fluid Dynamics (CFD) code Flownex to do integrated design and optimisation [1]. The system CFD representation of the cycle is shown in Figure 2.

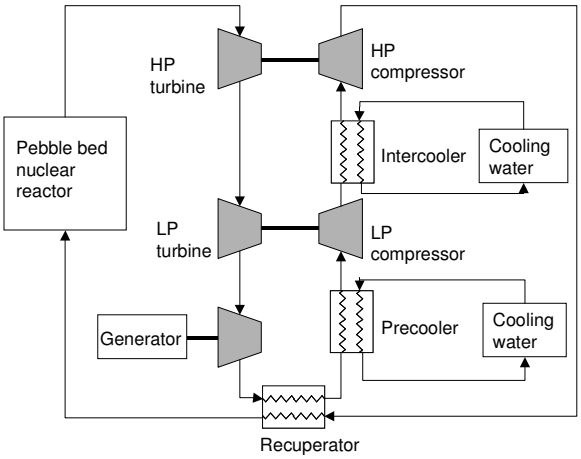

Figure 1: Schematic layout of the three-shaft recuperated Brayton cycle as used in the PBMR system.

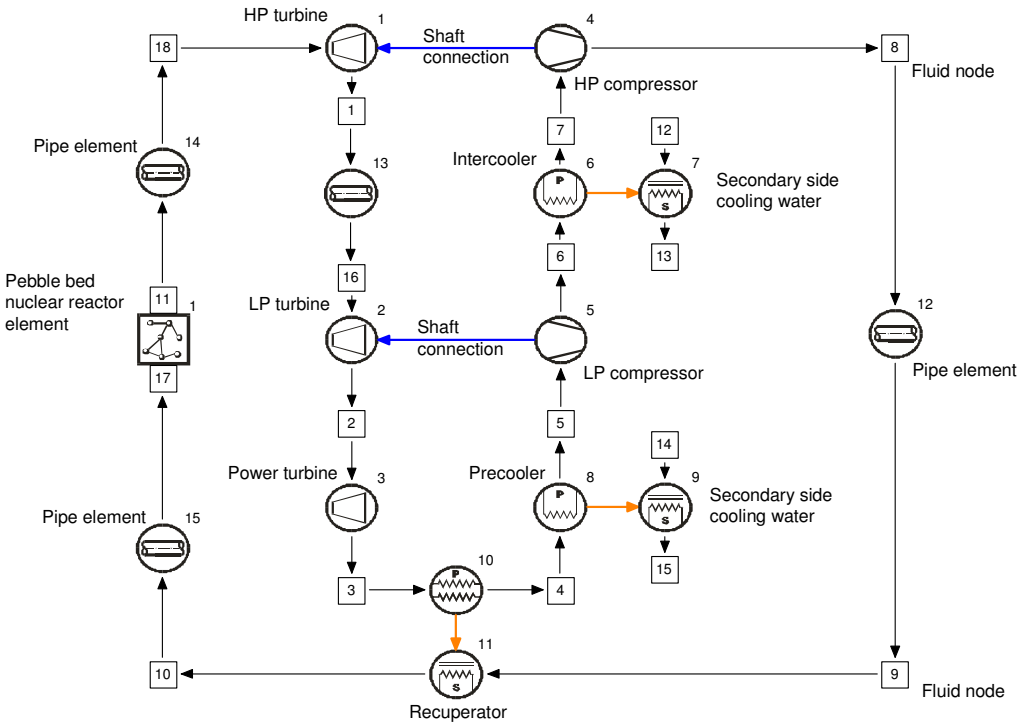

Figure 2: The system CFD representation of the PBMR power cycle in Flownex.

In the system CFD approach used in Flownex, components are modelled as one-dimensional flow and heat transfer elements for high calculation speed, while retaining adequate detail to determine their respective effects on the system. “Adequate detail” is a particularly challenging issue in the case of the nuclear reactor thermal-fluid (TF) model, as the reactor operation is very complex in itself and is profoundly affected by changes in the rest of the system. Also considering that the reactor is the energy source, it is clearly the most important component in the system.

From a safety point of view, the reactor is also the most critical part of the PBMR system, as it contains the fuel spheres that enclose the nuclear fission products. To prevent fission product release by diffusion, the maximum fuel temperature must under no circumstances rise above 1300°C. Therefore, a thermal-fluid (TF) system simulation model of the reactor must be able to calculate the maximum fuel temperature for all operating conditions. The importance of an accurate reactor TF model is underlined by the fact that fission heat generation is highly dependent on the fuel temperature and transient history.

Developing an accurate heat transfer model of the reactor is not a simple task because of the complexity of the phenomena involved. In the pebble bed, heat is generated in kernels inside

the fuel spheres. The heat is then conducted to the sphere surface where it is transferred to the helium by means of convection. In the bed itself, heat is transferred by means of conduction and interstitial radiation in the radial and axial directions.

Several approaches have been used to model such a pebble bed reactor. Verfondern [2] assumed a homogeneous bed, thereby using only three gas conservation equations. Becker and Laurien [3] used a heterogeneous model with three gas conservation equations and one energy conservation equation for the solids. Du Toit *et.al.* [1] implemented a heterogeneous model into Flownex with three gas conservation equations and two energy conservation equations for the solids: one equation accounting for conduction and radiation heat exchange between regions in the pebble bed and another for calculating the temperature distribution inside the fuel spheres. This paper investigates the validity of the approach taken by Du Toit *et. al.* [1] in the context of the system CFD methodology.

6 Qualitative discussion of different heat transfer mechanisms

Before contemplating reactor modelling approaches, the physics of pebble bed heat transfer is reviewed. As shown in Figure 3, the PBMR fuel consists of coated fissile material kernels, embedded in the graphite matrix of a fuel sphere.

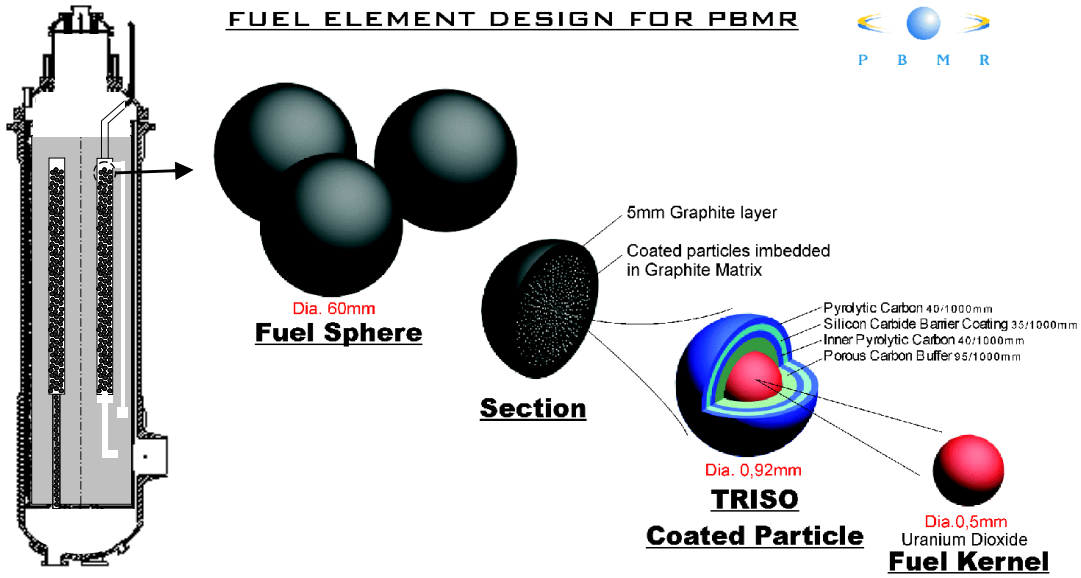

Figure 3: Composition of the PBMR fuel spheres.

The annular reactor core volume is filled with several thousand such spheres. In the fuel kernels, nuclear fission produces heat that is first conducted through the coatings to the graphite matrix, then to the surface of the fuel sphere. At the fuel sphere surface, gas is heated

by convection, while radiation exchanges heat with adjacent spheres. If a temperature gradient exists across the pebble bed, heat transport takes place by means of conduction through the fuel spheres in the bed and with additional interstitial radiation transfer.

It is essential to model these phenomena during system transients as the reactor thermal mass is linked by, and distributed between these different phenomena.

7 Classical CFD

One approach of modelling the thermal behaviour of the pebble bed reactor is to use a three-dimensional CFD code. Indeed, CFD calculations are very powerful and most CFD codes are capable of solving non-linear turbulent flow equations in complex three-dimensional geometries. However, solution of non-linear equations in complex geometries requires unstructured grids, sophisticated discretisation schemes and intricate data management, leading to very long computational times.

The forte of a classical CFD approach is component analysis where the focus is on detail in the spatial domain. The work by Van Staden *et. al.* [4] and Becker & Laurien [3] are examples of typical CFD application. Becker and Laurien investigated the temperature effect of misplaced fuel spheres in a pebble bed reactor with a dynamic centre column. Such a three-dimensional model of the reactor is necessary to investigate three-dimensional effects. However, it is not feasible in practice to use a CFD model for the numerous system-level "what-if" studies done during the design process. Becker and Laurien [3] reported, "a main memory of 1GB and about 20h computation time (cpu time) on one processor was necessary". In view of the fact that the PBMR design has changed to a fixed center column [5], misplacement of fuel elements is no longer possible, thereby also diminishing the need for three-dimensional simulations.

An additional consideration is that for a pebble bed, even CFD models assume a porous medium. This causes the flow equations to simplify considerably due to the dominance of the bed resistance. Given this simplification and the fact that the cost of the CFD computational overhead remains, the use of classical CFD offers very little benefit in this case.

Even if a very simplified CFD model is coupled to a system simulation code, information has to be exchanged either with an explicit or semi-implicit interface. This implies considerable programming effort to maintain conservation between the two codes. An explicit interface furthermore severely limits the timestep length in transient simulations[6].

In contrast to the classical CFD approach, the system CFD approach used in Flownex overcomes many of these hurdles. The system CFD approach is based on the classical CFD staggered grid discretisation. This discretisation has the advantage of excellent coupling between pressure and velocity, as scalar values (mass, pressure, temperature) are calculated at control volume centres (nodes), while vector quantities (e.g. velocity) are calculated at control volume faces (elements) [7].

In the system CFD approach, nodes representing fluid volumes or thermal masses are connected with one-dimensional heat and fluid flow elements to represent a thermal system. The type of element determines the pressure drop, mass and heat flow characteristics used in the conservation equations. Examples of elements are pipes, pumps, valves, heat exchangers, orifices, porous media flow resistances and solid conduction elements. The fundamental nature of the modelling approach enables simulation of phenomena such as pressure waves in gas flows, water hammer as well as convection, conduction and radiation heat transfer [8].

Networks can be arbitrarily structured to represent complex real-life situations. As shown in Figure 2, single components can also be modelled as sub-networks of nodes and elements, thereby providing freedom to match the level of detail of all components in a simulation.

The reactor model is a typical example of a component modelled as a sub-network, which is essentially the equivalent of a two-dimensional CFD model, but without the overhead associated with full CFD codes. Figure 4 shows how the reactor is modelled as a sub-network. This method has the advantage of a fully implicit coupling between the reactor and the rest of the system, so that the assembled network is solved as one system with the implicit pressure correction method [9].

Due to the implicit solution algorithm and implicit coupling between sub-networks, there is no timestep length constraint to ensure stability for transient simulations.

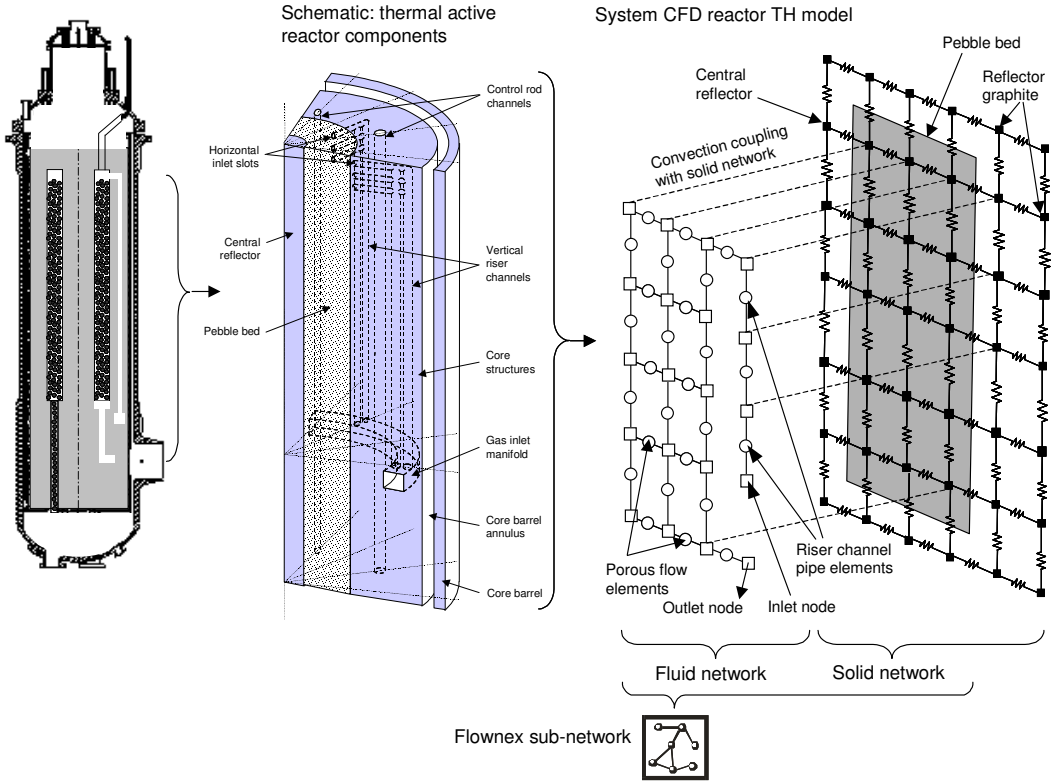

Figure 4: Diagram showing the network modelling approach for the reactor.

By combining different elements in different configurations, numerous topologies are possible to mimic the complex reactor behaviour. In the next section the validity of the current network topology is evaluated by comparison with two other possible topologies.

8 Current network model of the pebble bed

The current pebble bed network model is shown in Figure 5.

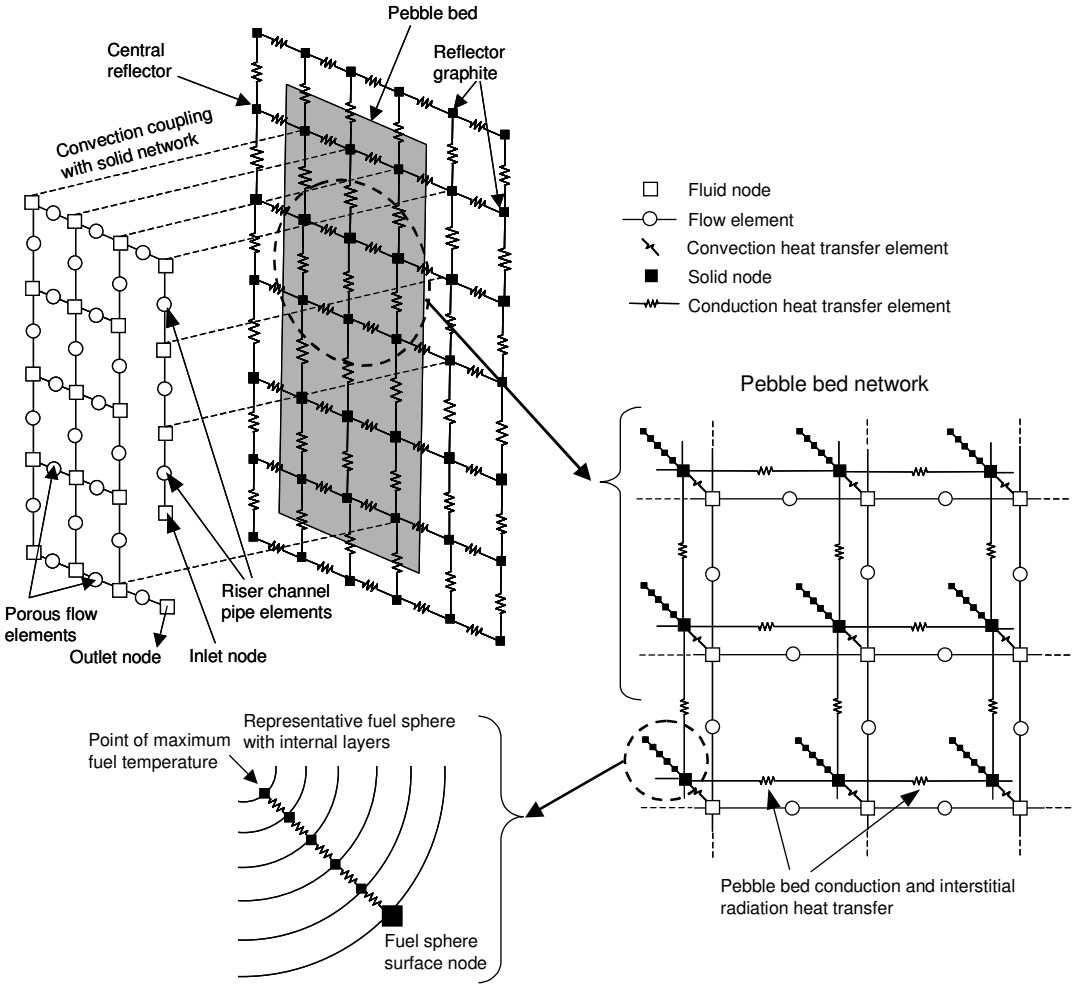

Figure 5: Current network model of the pebble bed core. It is a heterogeneous sphere model.

The current pebble bed reactor core model is the heterogeneous model described by Du Toit *et. al.* [1]. Axial symmetry is assumed, thereby discretising the pebble bed core in two-dimensional control volumes in cylindrical coordinates. The total volume of gas in a control volume is represented by a gas node, which is connected to other gas nodes with porous flow resistance elements. The pebble surface temperatures are represented by one representative solid node per control volume, from which convection to the gas occurs, as well as conduction and radiation within the pebble bed. Connected to each surface temperature node is a string of elements and nodes representing layers in a fuel sphere. This allows the calculation of the maximum fuel temperature within the sphere. The thermal mass of the solids is associated with the nodes in the representative fuel sphere.

A disadvantage of this topology is that the solid thermal mass within the sphere does not form part of the radial and axial heat conduction paths within the bed, so that this network could

have an inaccurate transient response associated with a sudden change in temperature gradient across the bed. However, if the conduction resistance inside the spheres is much smaller than the convection resistance between the sphere surface and the fluid, this approach (called the lumped capacity approach) will yield accurate results.

For transient conduction/convection systems, the Biot number is used to test the validity of the lumped capacity approach. The Biot number is an indication of the ratio of surface transfer resistance to internal conduction resistance, calculated as follows:

$$B_i = \frac{hL}{k} \tag{1.1}$$

with h being the surface convection coefficient, L the characteristic length of the solid and k its thermal conductivity. For the PBMR at full mass flow conditions, B_i is typically in the order of 0,3. Only if B_i is smaller than 0,1 can the sphere be treated as a lumped capacitance [10], so that it has to be subdivided. Aumiller [11] addressed the question as to the number of necessary subdivisions for a plane wall. His research produced the following formula:

$$\frac{1}{\beta_{\max}} = 0.338B_i + 5.2 \tag{1.2}$$

where β_{max} is the maximum length of the surface node, expressed as a fraction of the characteristic length L as described in Figure 6.

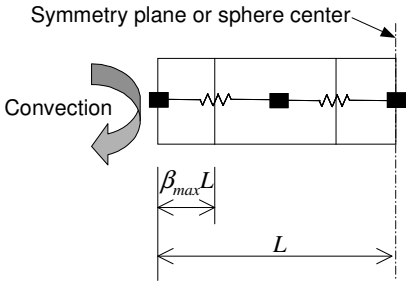

Figure 6: Illustrating the physical meaning of L and β_{max}.

Discretisations that adhere to this guideline can be expected to calculate the cumulative heat transfer within 20% of the analytical value for the full duration of the transient event.

Thus, for pebble bed spheres with a Biot number of 0,3, the surface layer should have a maximum length of 0,18L. In the current discretisation, the fuel sphere is divided radially in

five elements, so that the sphere surface node represents only $0{,}1L$ of the conduction length and the requirement is therefore adhered to.

To investigate the validity of the current approach for transient events, some other formulations will be investigated in the next sections.

9 First alternative

This first alternative is a heterogeneous model, in which the fuel spheres are modelled by a homogeneous porous solid, which is coupled to a coarser gas network by convection heat transfer resistances, as shown in Figure 7.

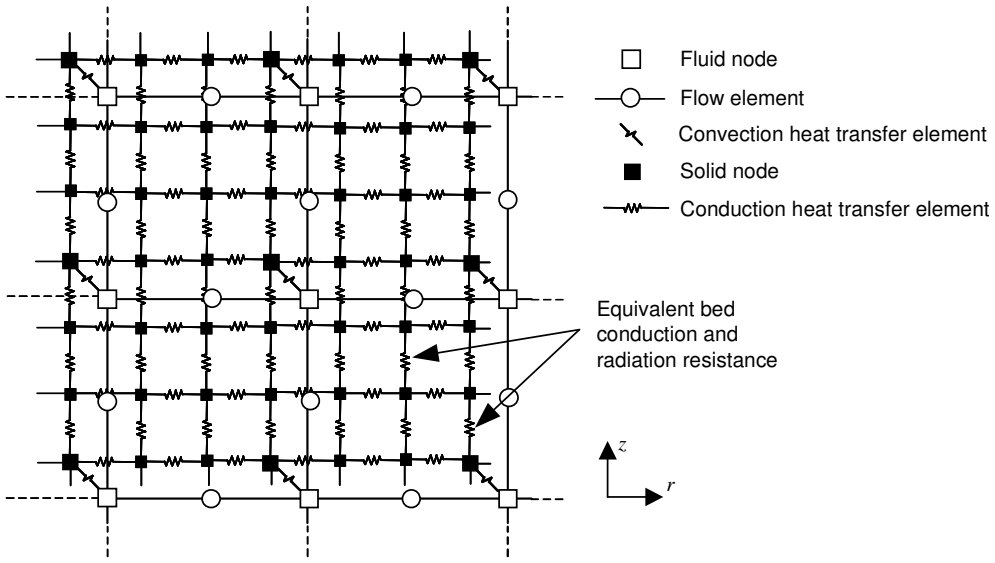

Figure 7: Network model of the core with a homogeneous solid representing the packed bed solids.

The conduction resistances in this topology represent the combined effect of conduction through the spheres, sphere contact resistances and interstitial radiation heat transfer. Because of the homogeneous bed assumption, no characteristic conduction length is applicable.

An advantage of this approach is that the capacitances are distributed within the radial and axial heat transfer paths so that transient response to gradients in the bed temperature will be calculated more accurately. A disadvantage though, is that information about the maximum temperature in a fuel sphere and the temperature difference between center and surface is not available.

10 Second alternative

This second alternative models the fuel spheres as solid annular rings, coupled to the flow network at the gaps as shown in Figure 8. In this topology, more effort is made with the radial bed conduction path than with the axial conduction path, as the radial heat flow path is of prime importance for the passive safety of the PBMR. This is due to the fact that radial conduction is the principal means of decay heat removal during loss-of-cooling incidents.

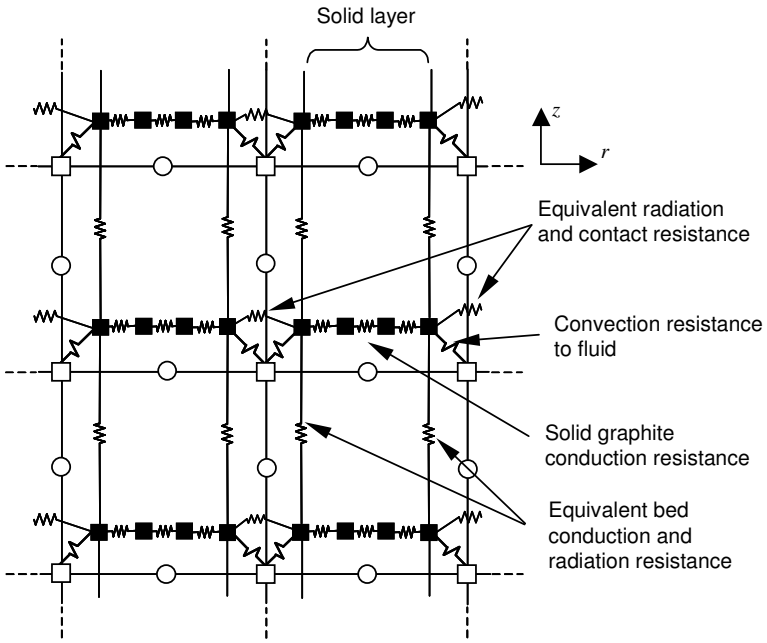

Figure 8: Heterogeneous layer representation of a packed bed.

The axial conduction resistances represent combined heat transfer mechanisms in the bed, while the radial conduction path is divided into solid resistances for the layers and resistances across the gaps representing interstitial radiation. The solid layer thickness is equal to the sphere diameter to have the same characteristic length.

This topology has the advantage that the thermal capacitances are distributed within the radial conduction path. Also, some indication is available of the temperature difference in the solids.

11 Assumptions and input parameters

One-dimensional networks will be used to test the transient response, as one-dimensional networks are simple to set up while still having the desired characteristics. The annular pebble bed is thus approximated as a one-dimensional radial system, as the principal temperature gradients occur radially. The annulus is divided into fourteen control volumes, so that each

control volume has a similar characteristic length, approximately equal to the diameter of a fuel sphere.

To isolate the effect of network topology, constant thermal conductivity is used throughout. The total thermal capacitance of each network is also the same, although it is differently distributed in each network. Approximating a spherical geometry with Cartesian elements resulted in a maximum difference of 0.94% in overall thermal capacitance between any two networks.

Common to all three topologies is the gas network and its convection coupling to the solid. The convection transfer coefficient is calculated with the correlation presented by Kugeler and Schulten [12]. The correlation by Zehner and Schlünder [13] is employed to determine equivalent bed radiation and conduction resistance.

For the heterogeneous solid sphere model shown in Figure 9 (current model), the resistances between surface nodes represent the combined effect of conduction through spheres, contact resistances and interstitial radiation in the bed. The bed resistances are not subdivided, as no mass is associated with them. Instead, the mass and transfer areas of all spheres in a control volume are associated with the six nodes and interconnecting thermal resistances within the representative sphere.

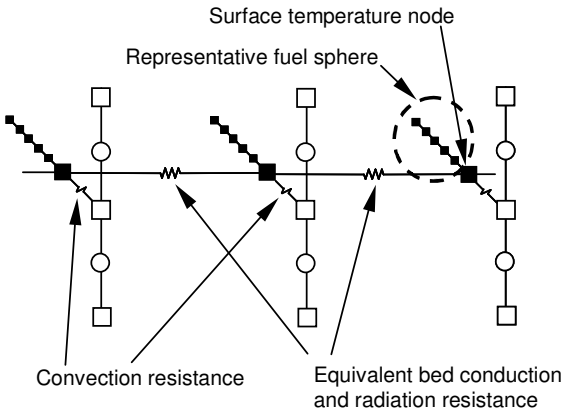

Figure 9: Part of the one-dimensional network of the heterogeneous solid sphere model.

In the homogeneous solid model in Figure 10 (first alternative), the conduction resistances represent the combined heat transfer effects in the bed, with the thermal mass evenly distributed between nodes. The conduction elements between convection points are subdivided into ten elements (only three subdivisions are shown in Figure 10).

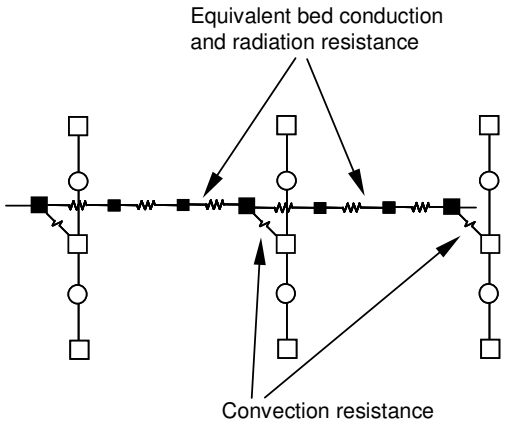

Figure 10: Part of the one-dimensional network with a homogeneous solid.

The heterogeneous layer model (second alternative) has the bed divided into solids and voids. Convection coupling with the gas elements is done at void interfaces, with an equivalent resistance representing interstitial radiation transfer and contact conduction. The solid layers have the same conductivity as solid graphite and are also subdivided in ten elements (only three subdivisions are shown in Figure 11). Thermal resistances are calculated so that the sum of solid and equivalent radiation resistances equal the combined conduction resistance of a packed bed.

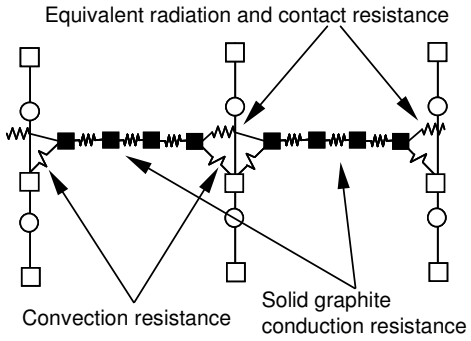

Figure 11: Part of the one-dimensional network of the heterogeneous layer model.

12 Steady-state results

To assure that the only source of difference in transient response is the network topology, the steady-state conduction of the three topologies have to be the equal. A radial temperature profile under no-flow conditions is shown in Figure 12. Less that 0.03% difference in steady-state radial heat flux was found between the networks.

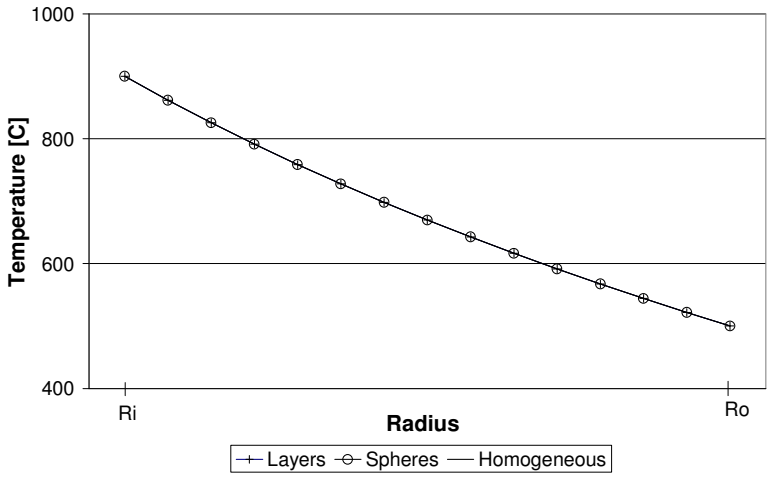

Figure 12: Steady-state radial surface temperature distribution as calculated with all three topologies. No heat generation and a fixed radial temperature difference over the bed.

13 Transient results

The temperature differences between networks are presented in the following non-dimensional form:

$$\Delta T[\%] = 100 \times \frac{T_1 - T_2}{T_\infty - T_0} \qquad (1)$$

T_1-T_2 is the difference between two discretisations at a certain location. T_0 is the steady-state temperature before the event and T_∞ the steady-state temperature after the event. For all cases in this paper, T_∞ - T_0 has a value of 400°C.

There are two conduction paths of which the response is dependant on the thermal mass configuration, the first being conduction from the bed surface into the solids and the second being the core radial conduction path.

The response of the conduction into the solids will be observed after a step change in gas temperature under full mass flow condition, as presented in Figure 13.

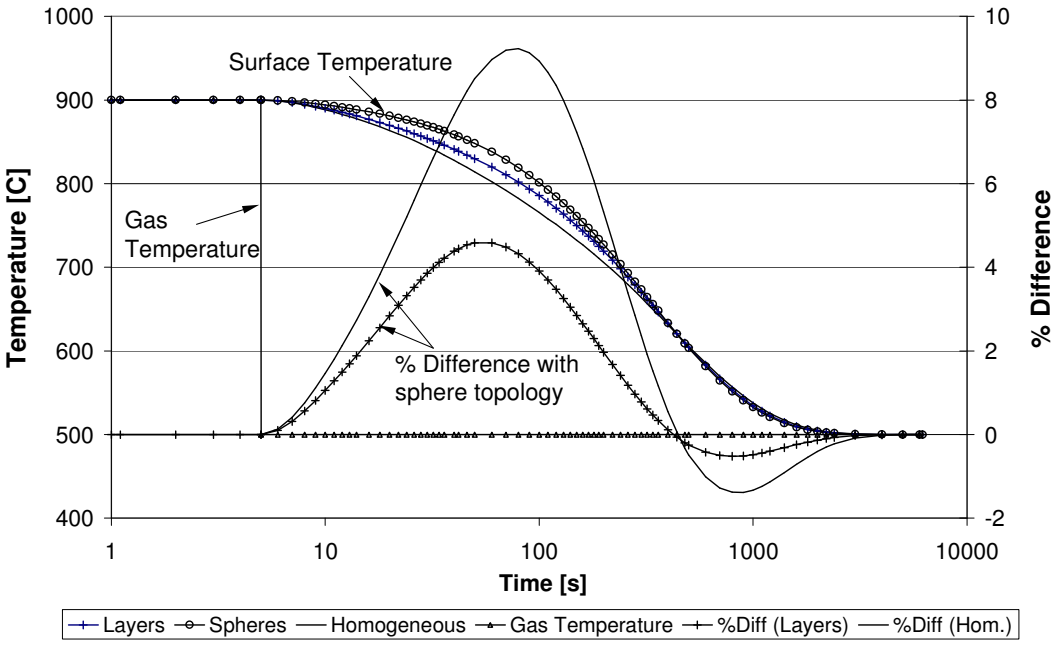

Figure 13: Surface temperature response to a change in gas temperature. The sphere model is used as reference for percentage difference calculation.

The lag of the sphere topology surface temperature is due its large surface node inertia. As illustrated in

Figure 17, the spherical geometry causes the thermal mass to be much more concentrated near the convection transfer points than with the other topologies. In the other topologies the mass is evenly distributed in the pebble bed cylindrical geometry. In the context of safety analysis, the initial time lag of the sphere topology is not significant, as repeated real-life transients are much more gradual than the simulated step temperature change.

To test the response of the core radial conduction path, the pebble bed outer temperature is fixed at 500°C, while the pebble bed center temperature is suddenly increased to 900°C under no-flow conditions. Temperatures at several locations in the bed are plotted in Figure 15. Percentage differences between the topologies are shown in Figure 16.

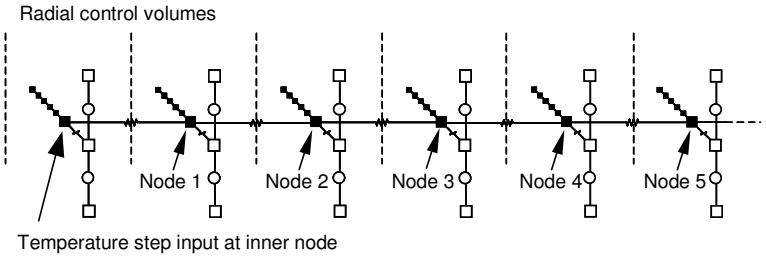

Figure 14: Indication of temperature result locations in Figure 15 (sphere topology shown).

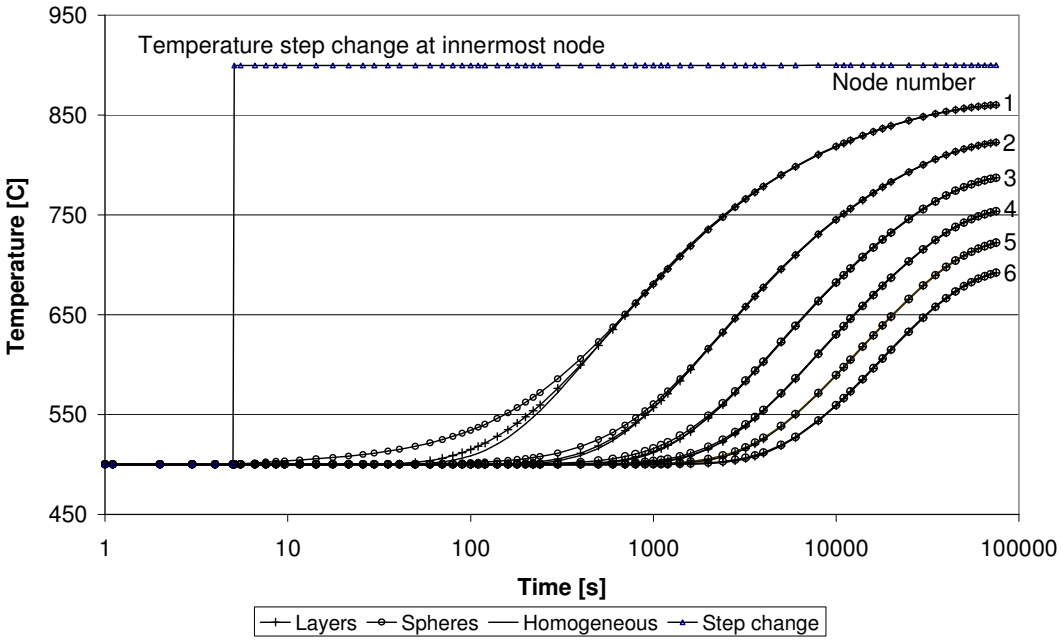

Figure 15: Surface temperature response at different annular layers from the pebble bed center.

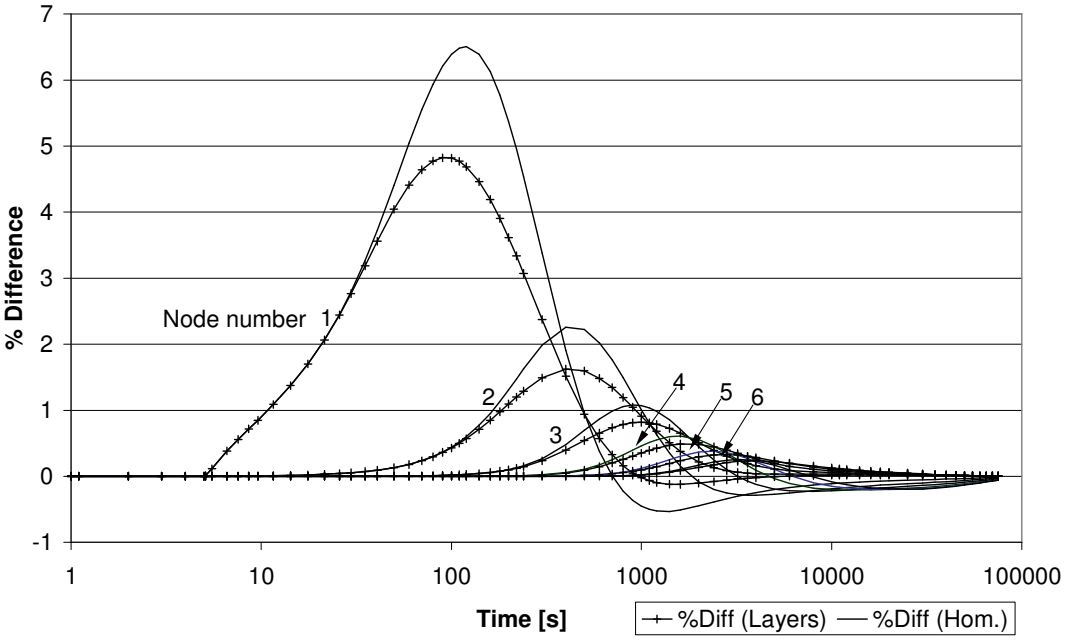

Figure 16: Percentage difference between topologies for the results in Figure 15. The sphere topology is used as reference.

It is seen in Figure 15 that the sphere topology initially has a faster response than the other configurations. This can be expected, as the layer and homogeneous bed topologies have the total thermal mass on the conduction path, while the sphere topology has considerable mass

distributed away from the main conduction path. This also explains why the sphere topology surface temperature takes longer to stabilise, as is only seen in Figure 16. While the temperature difference is up to 6,5% at the first node, at the third node the maximum percentage difference between any two topologies is at most one percent.

14 Heat generation

Under full coolant flow, neutronic heat generation causes a difference between fuel sphere internal and surface temperature, as discussed in Paragraph 6. For this reason, the average temperature of the reactor core mass is higher than the surface temperature, so that calculation of stored core thermal energy can not be based on surface temperature.

However, for the homogeneous topology the mass in a control volume is assumed to be at surface temperature, so that no stored heat due to sphere internal temperature distributions could be taken into account. This limits the homogeneous topology to steady-state simulations and transient events with no coolant flow, in which temperature gradients exist only at bed-level instead of control volume level.

With the heterogeneous layer topology, a temperature distribution is calculated inside the solids, with constant heat generation per volume applied at all solid nodes. But since the spatial distribution of thermal mass and temperature is not spherical, the stored energy is not expected to be accurate.

In the heterogeneous sphere topology, heat generation is also applied at a constant rate per volume at the appropriate nodes representing sphere internal mass. The sphere internal temperature distribution is calculated along with a correct mass distribution, so that the stored energy is expected to be accurate.

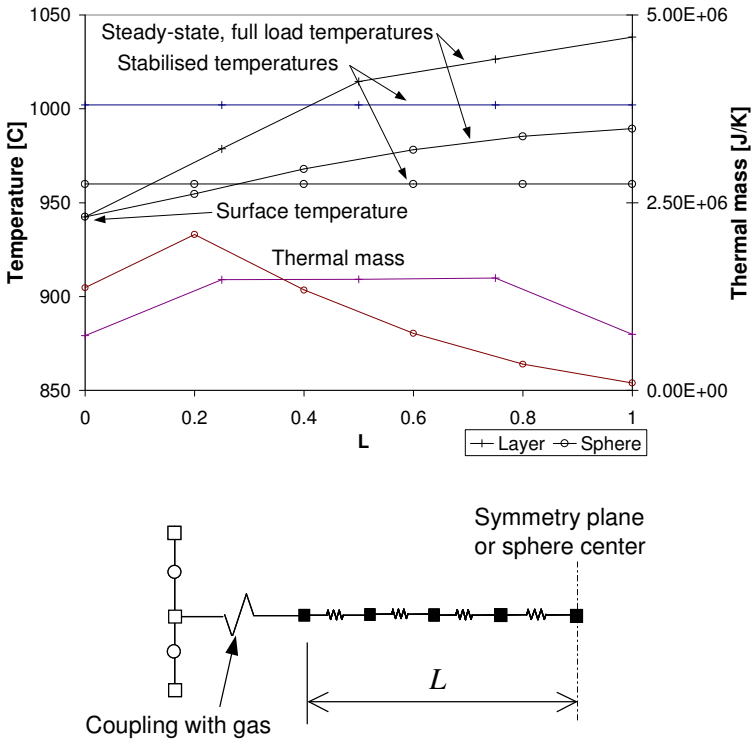

Figure 17: Control volume temperature and mass distributions for the layer and sphere topologies.

The stored thermal energy is very important as it determines the average local temperature in the bed when coolant flow would stop, as is the case with a loss-of-forced-cooling incident. This is illustrated in

Figure 17, where the "stabilised" temperature is reached when flow and power input to the pebble bed is suddenly stopped. The stored thermal energy distributes evenly so that an isothermal condition develops. As indicated, the layer topology results in a higher temperature (1002°C) than the sphere topology (960°C) and is therefore the more conservative option, though less accurate.

15 Conclusion

The versatility of the system CFD approach was illustrated by showing three different possible topologies for a pebble bed reactor core model. Despite the differences in network layout, the largest temperature difference between any two topologies in a transient simulation without heat generation was 9%. On the basis of the general good agreement between such diverse topologies, all three topologies are accepted as valid models of a pebble bed. However, the homogeneous topology was found to have very limited applicability in cases with heat generation. Of the three topologies, the sphere topology is the most useful as it provides the

most information, namely the temperature distribution in the fuel spheres as well as an accurate calculation of stored thermal energy. It is therefore considered the most suitable topology for a reactor core thermal-fluid simulation model.

16 Acknowledgements

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17 References

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