The Analysis of the OECD/NEA/NSC PBMR-400 Benchmark Problem Using PARCS-DIREKT

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Abstract

The OECD/NEA/NSC PBMR-400 benchmark problem was developed to support the validation and verification efforts for the PBMR design. This paper describes the analysis of this problem using the PARCS-DIREKT coupled code system. The benchmark problem involved the use of two different cross-section libraries, one which was generated from a VSOP equilibrium core calculation and has no dependence on core conditions. The second library provides for dependence on five state parameters and was designed for transient analysis. The paper here reports the steady-state cases using the VSOP set of cross-sections. The results are shown to be in good agreement with those of VSOP. Also reported here are the results of the steady-state thermal-hydraulic DIRECKT solution with a given power profile obtained from VSOP equilibrium core calculation. This analysis provides some insight as to the most important parameters in the design of PBMR-400.

KEYWORDS: PBMR, PARCS, DIREKT, Benchmark, VSOP.

1. Introduction

The Pebble Bed Modular Reactor (PBMR) is a high-temperature, helium-cooled and graphite-moderated reactor designed by PBMR Pty. Ltd. Company of South Africa. The final design has a thermal power of 400MW and contains a solid central reflector and three defueling chutes at the bottom of the core. Helium enters the core at a temperature of 500^{o}C and leaves the core at about 900^{o}C.

In order to support the validation and verification of methods used to analyze the PBMR, a set of benchmark problems has been defined that focuses on coupled neutronics thermal-hydraulics code-to-code comparison. The benchmark study was designed to provide a detailed understanding of some the methods and modeling limitations and approximations used in PBMR analysis.

This paper presents the analyses of the PBMR-400 benchmark problem with PARCS-DIREKT coupled code. PARCS is a three dimensional core simulator which solves steady-state and time-dependent multi-group neutron diffusion and SP3 transport equations in various geometries [1]. To obtain the thermal feedback and perform the transient analyses of this benchmark PARCS was coupled to thermal-hydraulics code DIREKT which solves the steady-state and time dependent heat transfer and fluid flow in two dimension (r,z)[2].

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2. PBMR-400 Benchmark Problem

2.1 Simplifications and Specifications

The reactor core is modeled in two-dimensions (r,z) with some simplifications such as flattening the pebble bed's upper surface and removal of the bottom de-fueling chutes which results in a flat bottom reflector. The pebble flow is simplified to be in parallel channels and at equal speed. The control rods in the side reflector are modeled with a given B-10 concentration as a cylindrical skirt. The void regions are treated with direction dependent diffusion coefficients where the coefficients are specified as a part of benchmark problem. In the thermal-hydraulic design, the stagnant helium and air is specified between the core barrel and RPV and RPV and heat sink, respectively. The coolant flows upwards from the inlet through the helium channels to the upper plenum and flows downwards through the pebble bed to the outlet plenum. No reflector cooling, leakage paths and external sources are defined and the thermal properties except the pebble bed are assumed to be constant.[3]

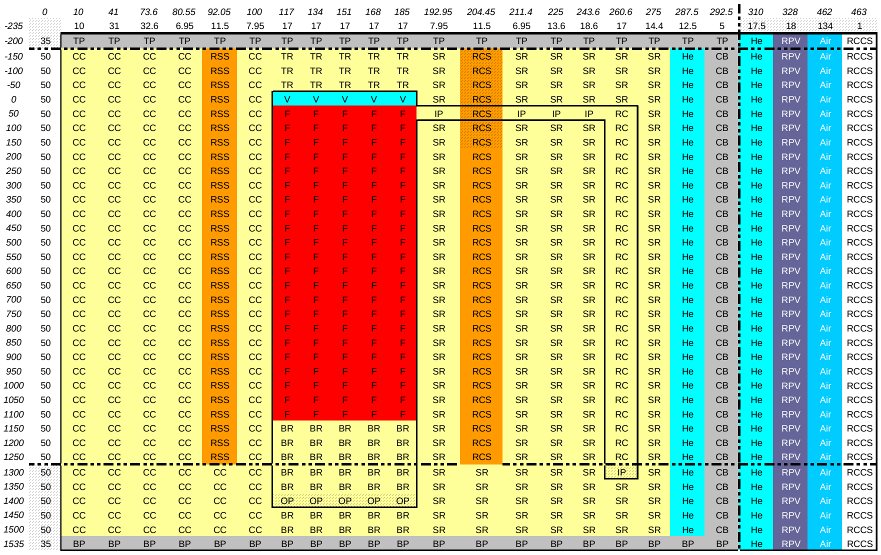
2.2 Cross-section Libraries

Two different sets of cross-sections are provided for the benchmark problem. The first one is a simplified set with no dependence on core conditions and was generated from a VSOP equilibrium core calculation. This set was used in steady state problems and was useful to test the correct implementation of the routines that process the cross sections read from the tables. The second set contains cross-sections as a function of five state parameters and was intended for use in the transient cases. The five state parameters are; fuel temperature, moderator temperature, fast buckling, thermal buckling and xenon concentration. The ranges for each parameter were selected considering the normal operation and accident conditions.

2.3 Reactor Layout and Dimensions

Figure 1 shows the reactor layout and dimensions with definition in the key.

Figure 1: Reactor Layout



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-235		10	31	32.6	6.95	11.5	7.95	17	17	17	17	17	7.95	11.5	6.95	13.6	18.6	17	14.4	12.5	5	17.5	18	134	1
-200	35	TP	TP	TP	TP	TP	TP	TP	TP	TP	TP	TP	TP	TP	TP	TP	TP	TP	TP	TP	TP	He	RPV	Air	RCCS
-150	50	CC	CC	CC	CC	RSS	CC	TR	TR	TR	TR	TR	SR	RCS	SR	SR	SR	SR	SR	He	CB	He	RPV	Air	RCCS
-100	50	CC	CC	CC	CC	RSS	CC	TR	TR	TR	TR	TR	SR	RCS	SR	SR	SR	SR	SR	He	CB	He	RPV	Air	RCCS
-50	50	CC	CC	CC	CC	RSS	CC	TR	TR	TR	TR	TR	SR	RCS	SR	SR	SR	SR	SR	He	CB	He	RPV	Air	RCCS
0	50	CC	CC	CC	CC	RSS	CC	V	V	V	V	V	SR	RCS	SR	SR	SR	SR	SR	He	CB	He	RPV	Air	RCCS
50	50	CC	CC	CC	CC	RSS	CC	F	F	F	F	F	IP	RCS	IP	IP	IP	RC	SR	He	CB	He	RPV	Air	RCCS
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200	50	CC	CC	CC	CC	RSS	CC	F	F	F	F	F	SR	RCS	SR	SR	SR	RC	SR	He	CB	He	RPV	Air	RCCS
250	50	CC	CC	CC	CC	RSS	CC	F	F	F	F	F	SR	RCS	SR	SR	SR	RC	SR	He	CB	He	RPV	Air	RCCS
300	50	CC	CC	CC	CC	RSS	CC	F	F	F	F	F	SR	RCS	SR	SR	SR	RC	SR	He	CB	He	RPV	Air	RCCS
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1250	50	CC	CC	CC	CC	RSS	CC	BR	BR	BR	BR	BR	SR	RCS	SR	SR	SR	RC	SR	He	CB	He	RPV	Air	RCCS
1300	50	CC	CC	CC	CC	CC	CC	BR	BR	BR	BR	BR	SR	SR	SR	SR	SR	IP	SR	He	CB	He	RPV	Air	RCCS
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1400	50	CC	CC	CC	CC	CC	CC	OP	OP	OP	OP	OP	SR	SR	SR	SR	SR	SR	SR	He	CB	He	RPV	Air	RCCS
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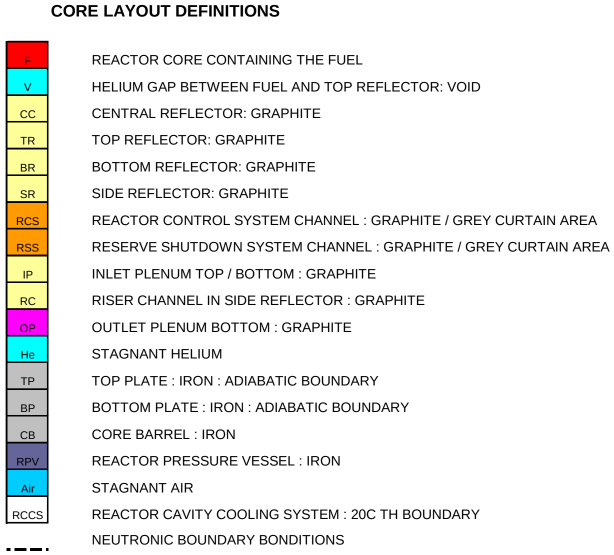
1500	50	CC	CC	CC	CC	CC	CC	BR	BR	BR	BR	BR	SR	SR	SR	SR	SR	SR	SR	He	CB	He	RPV	Air	RCCS
1535	35	BP	BP	BP	BP	BP	BP	BP	BP	BP	BP	BP	BP	BP	BP	BP	BP	BP	BP	BP	BP	He	RPV	Air	RCCS



CORE LAYOUT DEFINITIONS

F	REACTOR CORE CONTAINING THE FUEL
V	HELIUM GAP BETWEEN FUEL AND TOP REFLECTOR: VOID
CC	CENTRAL REFLECTOR: GRAPHITE
TR	TOP REFLECTOR: GRAPHITE
BR	BOTTOM REFLECTOR: GRAPHITE
SR	SIDE REFLECTOR: GRAPHITE
RCS	REACTOR CONTROL SYSTEM CHANNEL : GRAPHITE / GREY CURTAIN AREA
RSS	RESERVE SHUTDOWN SYSTEM CHANNEL : GRAPHITE / GREY CURTAIN AREA
IP	INLET PLENUM TOP / BOTTOM : GRAPHITE
RC	RISER CHANNEL IN SIDE REFLECTOR : GRAPHITE
OP	OUTLET PLENUM BOTTOM : GRAPHITE
He	STAGNANT HELIUM
TP	TOP PLATE : IRON : ADIABATIC BOUNDARY
BP	BOTTOM PLATE : IRON : ADIABATIC BOUNDARY
CB	CORE BARREL : IRON
RPV	REACTOR PRESSURE VESSEL : IRON
Air	STAGNANT AIR
RCCS	REACTOR CAVITY COOLING SYSTEM : 20C TH BOUNDARY
- - -	NEUTRONIC BOUNDARY BONDITIONS

2.4 Boundary Conditions and Material Properties

The neutronics and thermal-hydraulics boundary conditions are given in Tables 1 and 2 respectively. Tables 3, 4, 5 and 6 shows the material properties used in the calculations.

Table 1: Neutronics Boundary Conditions

#	Description	Unit	Value
	Neutronics model boundaries		
1	Radial; outer boundary of the reactor barrel	m	2.925
2	Top (beyond 150 cm of top reflector, i.e. 2 metres above the core)	m	- 2.0
3	Bottom (beyond 150 cm of bottom reflector)	m	12.5
4	Type of boundary conditions (on all boundaries)		BLACK

Table 2: Thermal Hydraulics Boundary Conditions

	Thermal Hydraulic model boundaries		
1	Radial	m	4.62
2	Top (from top of fuel) i.e. top plate	m	2.0
3	Bottom (from bottom of core) i.e. bottom plate	m	4.0
	Thermal Hydraulic boundary conditions		
4	Radial (Constant Temperature)	ºC	20
5	Top and Bottom	-	Adiabatic

Table 3: Emissivities

#	Description	Unit	Value
1	The emissivity of the fuel and graphite spheres.		0.8
2	The emissivity of the graphite structures and carbon.		0.8
3	The emissivity of the core barrel: Type 316 Stainless Steel		0.8
4	The emissivity of the RPV		0.8

Table 4: Specific Heat Capacities

#	Description	Unit	Value
1	Fuel and graphite spheres as well as reflector graphite (or 3.02 W.sec.cm^{-3}.K^{-1} for a density of 1.78 g.cm^{-3})	J. kg^{-1} K^{-1}	1697
2	Reactor Pressure Vessel (or 4.095 W.sec.cm^{-3}.K^{-1} for a density of 7.8 g.cm^{-3})	J. kg^{-1} K^{-1}	525
3	Core Barrel (or 4.212 W.sec.cm^{-3}.K^{-1} for a density of 7.8 g.cm^{-3})	J. kg^{-1} K^{-1}	540
4	Specific heat capacity of helium	J. kg^{-1} K^{-1}	5190
5	Specific heat capacity of air	J. kg^{-1} K^{-1}	1006

Table 5: Thermal Conductivities

#	Description	Unit	Value
1	Pebble bed (effective) Simplified with constant thermal conductivity, heat capacity and with zero fast fluence dose	W m^{-1} K^{-1}	Zehner-Schlünder correlation
2	Reflector, graphite spheres and fuel graphite. (actual value is a function of temperature, fast fluence and irradiation temperature)	W m^{-1} K^{-1}	20.0
3	Reactor Pressure Vessel (SA 508) constant	W m^{-1} K^{-1}	38.0
4	Core Barrel (Type 316 Stainless Steel) constant	W m^{-1} K^{-1}	17.0
5	Helium (all areas; assumed at pressure and inlet temperature)	W m^{-1} K^{-1}	0.30
6	Air (atmospheric conditions)	W m^{-1} K^{-1}	0.03
7	Fraction of contact area between spheres (vs total contact area)	%	1.6

Table 6: Hydraulic Diameters

#	Description	Unit	Value
1	Risers channels: Side porous region	cm	17.0
2	Top porous region	cm	7.7
3	Bottom porous region	cm	7.0
4	Top void area	cm	170
5	Inlet (top and bottom) plenums	cm	33.5
6	Outlet plenum	cm	14.4

3. Results and Analysis

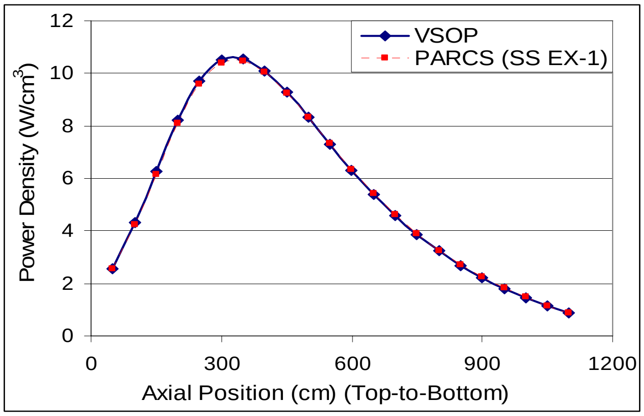
3.1 Steady-State Case 1

The analysis of steady-state case 1 was performed by using standalone PARCS with the VSOP cross section set. The void regions above the core and next to the side reflector were treated by using direction dependent diffusion coefficients as described in the benchmark document. [3] When the VSOP computational mesh is used in PARCS, the eigenvalue of the problem differs only 8 pcm from the VSOP result. The steady state eigenvalue and maximum power density are given in Table 1. The comparison of the power profile obtained by PARCS and VSOP is shown in Figure 2.

Table 1: Comparison of steady-state results

Calculation Tool	k_{eff}	Max. Power Density
PARCS	1.00008	10.48
VSOP	1.00000	10.55

Figure 2: Power density profile in the inner core channel



3.2 Steady-State Case 2

Case 2 analyzed by the standalone DIREKT code. The power density in the core is provided as a benchmark specification and obtained from VSOP equilibrium core calculation. The material properties given in Tables 3-6 were used with the boundary conditions shown in Table 2.

Some of the calculated reactor parameters are shown in Table 7. The gas inlet and mass flow shown were provided as problem input parameters. The axial temperature profiles in the inner core channel, where the maximum temperatures are observed are shown in Fig. 3. The Doppler temperature was defined as the average temperature in the fuel matrix of the pebble and the moderator temperature was defined as the average temperature of the pebble including the outer graphite shell. Figure 4 shows the solid temperature profile over the whole core.

Table 7: Calculated T/H Paramaters

Gas Inlet T (^{o}C)*	500.0
Gas Outlet T (^{o}C)	898.4
Mass Flow Rate (kg/s)*	192.7
Pressure Drop (kPa)	296.8
Max. Fuel Temp. (^{o}C)	1006.7
Max. Surface Temp (^{o}C)	948.8
Max. Gas Temp. (^{o}C)	945.6

***Specified as Problem Input**

Figure 3: Axial temperature profiles in the inner core channel

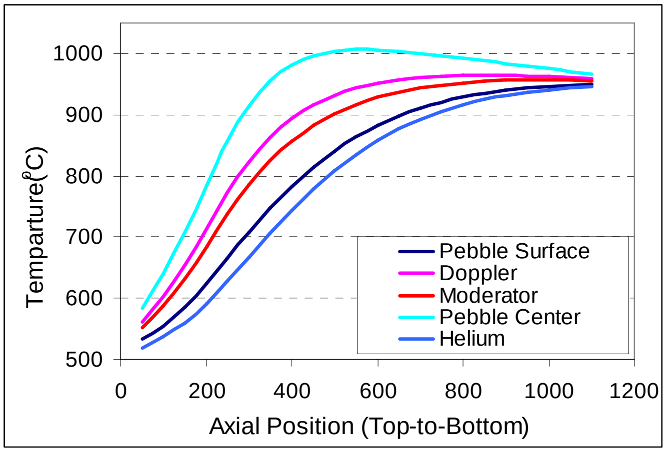
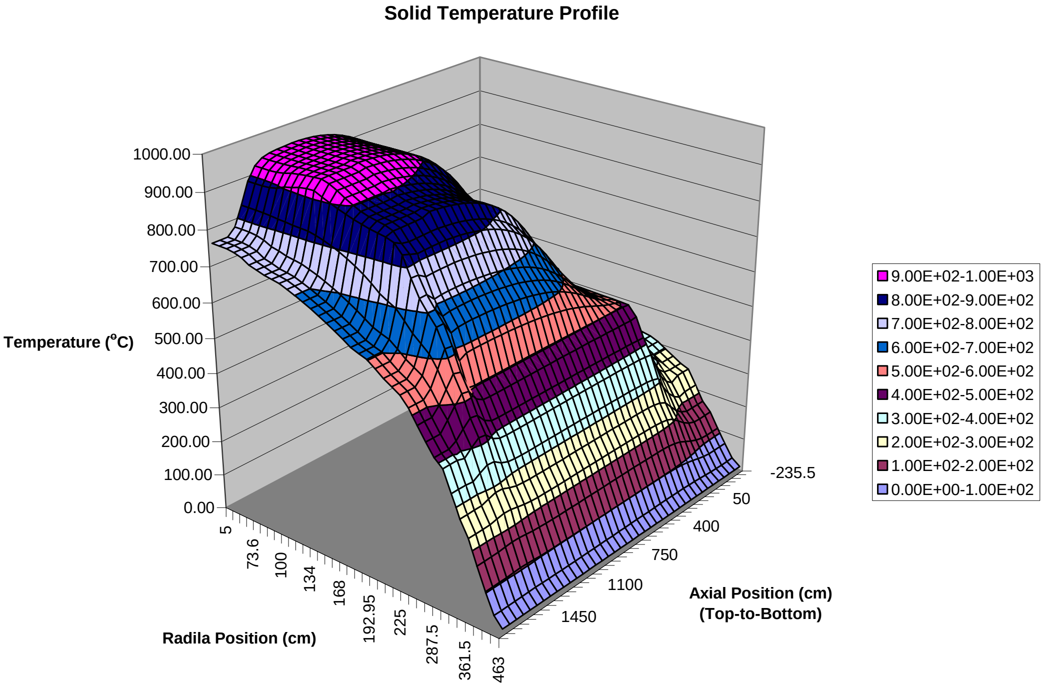


Figure 4: Solid Temperature Profile



4. Conclusion

The first two steady-state cases of the PBMR-400 benchmark problem were analyzed with the codes PARCS and DIREKT. The results of the first case in which the VSOP cross-sections were used in PARCS was in good agreement with the results from the VSOP solution from which these cross-sections were extracted. In case 2 the steady-state thermal-hydraulic calculation was performed in DIREKT with the power profile obtained from the VSOP equilibrium core calculation. The maximum fuel temperature observed in the calculation was about 1000°C and the maximum pebble surface temperature was below 950°C.

References

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