THERMODYNAMIC ANALYSIS OF PBMR PLANT

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The thermodynamic analysis of a PBMR is presented for various pressures and temperatures values. The design parameters of the components of the power plant are calculated and an optimum cycle for the maximum thermal efficiency is sought for.

Introduction

The thermodynamic analysis of a PBMR is of importance at the design stage. Such an analysis will not be complete if the component design is not included in the analysis as well as the economic analysis. Unfortunately a complete set of design and economical data are not easy to acquire. There are various design parameters available in the open literature that are not in agreement with each other[1,2]. Thus a detailed analysis of the thermodynamic cycle and design of the components of such a cycle is of academic interest as well as practical use. A computer program capable of optimizing a PBMR plant for a limited amount of input parameters is presented as a preliminary result of an ongoing project.

Modeling

The PBMR power plant has two turbocompressors, a power turbine, a recuperator and two coolers and the pebble bed reactor. The simplified block diagram of the plant is shown in Fig. 1. The T-s diagram of the Brayton cycle of this power plant is presented in Fig 2.
All heat exchangers, recuperator and two coolers, are designed in such a way that they have the physical dimensions very similar to ones given in the literature. [1]

Calculations

The computer code requests the properties at the inlet of the low pressure compressor and at the outlet of the reactor core. Then the code calculates the number of compressors needed to achieve the required compression ratio and the design parameters of the compressors, like number of stages, blade angles, etc. Intercooler design parameters, like the dimensions of the intercooler, pressure drops of both sides, water flow rate, etc. are also calculated. A rough calculation for the recuperator design parameters are performed to determine core inlet properties.
A detailed core thermal hydraulic modeling of the core is not performed at this point of time but will be added to the code in the near future. The core inlet and outlet temperatures are taken as metallurgical and radiation damage limits for the graphite internals.
Thermodynamic state and design parameters of the turbines driving the compressors and the generator and the recuperator inlet properties are calculated. The exhaust pressure of the power

turbine is changed such that the new cycle has a better thermal efficiency than the initial guess. This iterational procedure is terminated when the highest thermal efficiency is obtained for the given input temperatures and pressures.

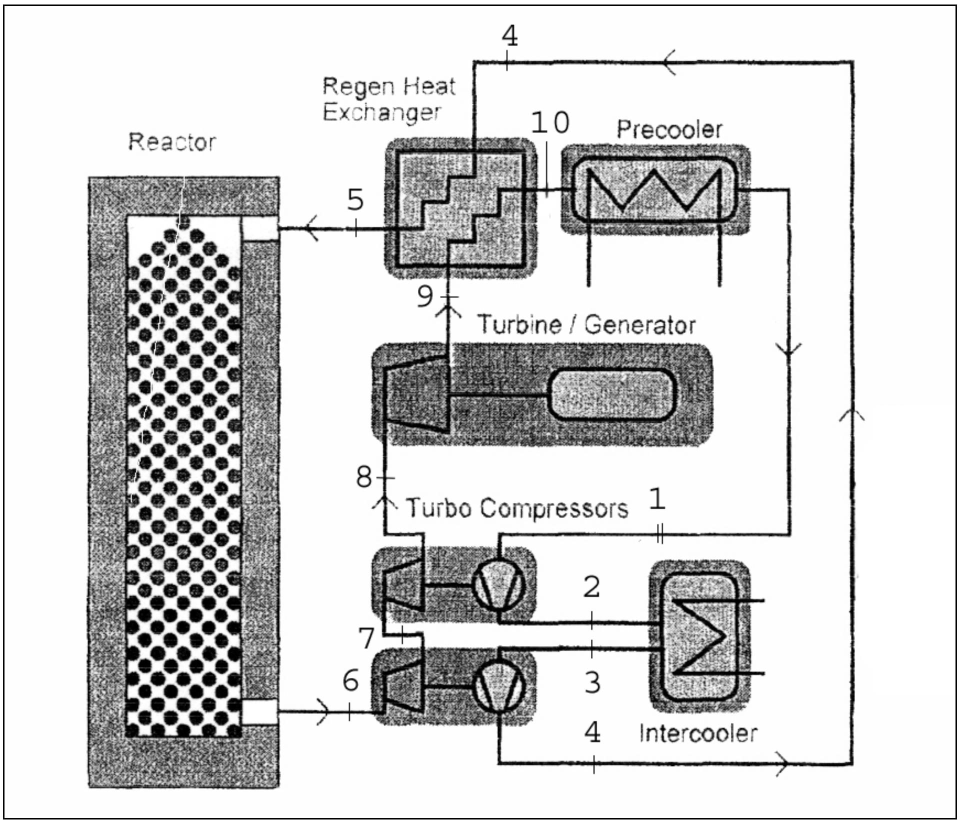

Figure 1. Layout of a Typical PMBR Power Conversion System

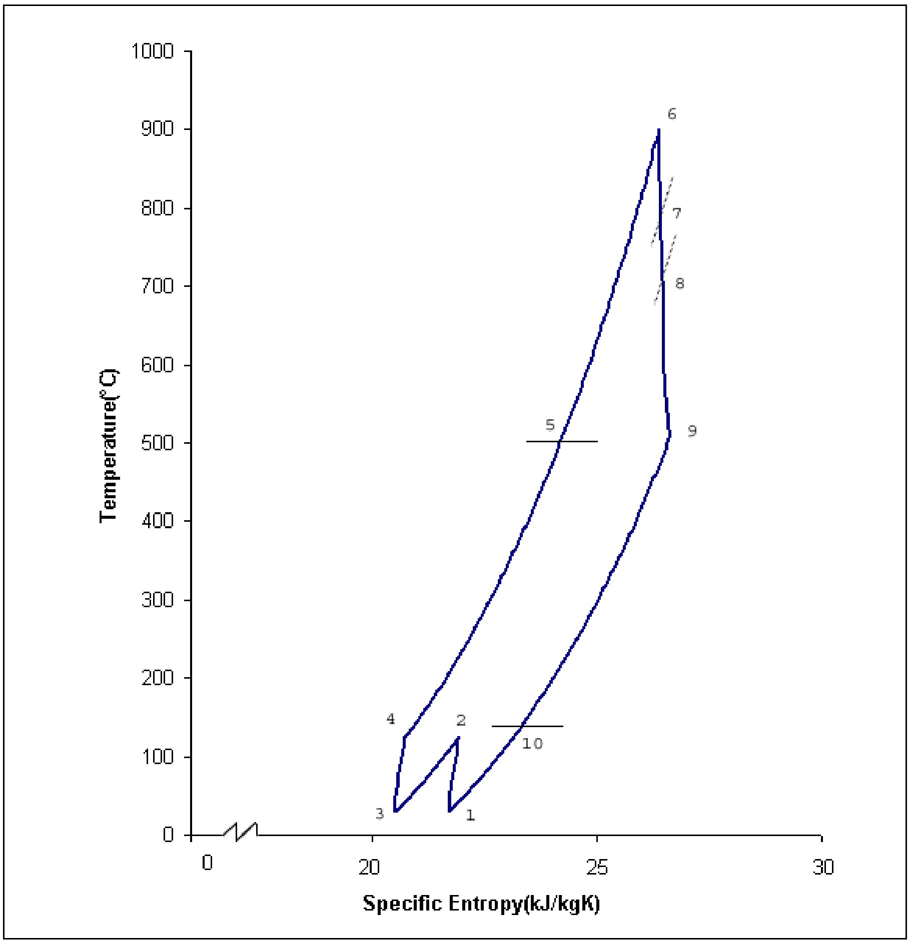

Figure 2. T-S Diagram of a typical PBMR system

Results

A sample case for the maximum operation pressures of 7, 8.5, 10 MPa and 30ºC low pressure compressor inlet temperature are run for the core outlet temperature of 900ºC and 950ºC and core inlet temperature of 500ºC. The results, pressure and temperature values of each points on the Brayton cycle, required and generated power for compressors, coolant pumps and turbines and the overall thermal efficiency are presented in Table 1, and the detailed components data for 8.5 MPa and 900ºC are presented in Table 2.

Table 1. Thermodynamic Analysis of PBMR System

P_{max} (MPa)		7.0		8.5		10.0	
T_{max} (ºC)		900.00	950.00	900.00	950.00	900.00	950.00
1	P (MPa)	2.20	1.9500	2.6600	2.35	3.17	2.80
	T (ºC)	***30.00***	***30.00***	***30.00***	***30.00***	***30.00***	***30.00***
2	P (MPa)	3.92	3.69	4.75	4.45	5.63	5.29
	T (ºC)	138.84	151.09	138.88	141.61	126.36	144.65
3	P (MPa)	3.91	3.68	4.73	4.43	5.62	5.28
	T (ºC)	30.00	30.00	30.00	30.00	30.00	30.00
4	P (MPa)	7.00	7.00	8.50	8.51	10.00	10.00
	T (ºC)	128.60	142.65	128.53	141.41	126.85	137.46
5	P (MPa)	***7.0000***	***7.0000***	***8.5000***	***8.5000***	***10.0000***	***10.0000***
	T (ºC)	***500.00***	***500.00***	***500.00***	***500.00***	***500.00***	***500.00***
6	P (MPa)	***6.8250***	***6.8250***	***8.3250***	***8.3250***	***9.8250***	***9.8250***
	T (ºC)	***900.00***	***950.00***	***900.00***	***950.00***	***900.00***	***950.00***
7	P (MPa)	5.36	5.23	6.54	6.38	7.75	7.63
	T (ºC)	801.40	837.25	801.47	837.59	803.15	842.54
8	P (MPa)	3.92	3.74	4.79	4.69	5.90	5.56
	T (ºC)	686.83	709.88	686.86	720.10	701.72	721.85
9	P (MPa)	2.22	1.97	2.68	2.37	3.19	2.82
	T (ºC)	511.92	511.82	508.92	507.94	511.54	510.02
10	P (MPa)	2.22	1.97	2.68	2.37	3.19	2.82
	T (ºC)	137.5	154.10	135.14	146.92	136.76	145.10
W_{c1} (MW)		79.12	88.03	79.15	81.14	70.05	83.35
W_{c2} (MW)		71.68	81.90	71.63	81.72	70.41	78.12
W_{p1} (MW)		4.59	5.74	4.29	4.59	3.28	4.59
W_{p2} (MW)		5.32	7.02	4.73	5.96	4.64	5.35
W_t (MW)		114.76	129.94	116.74	139.20	124.78	138.98
η		0.36	0.36	0.37	0.39	0.40	0.39

Table 2. Detailed Component Properties of PBMR System

LOW PRESSURE COMPRESSOR		
Design Parameters		
Max. Blade Tip Speed	(m/s)	360.00
Polytropic Efficiency		0.90
Compressor Inlet Values		
Inlet Temperature	(ºC)	30.00
Inlet Pressure	(MPa)	2.66
Inlet Blade Tip Speed	(m/s)	349.77
Inlet He Density	(kg/m³)	3.73
Inlet Tip Radius	(m)	0.24
Inlet Blade Height	(m)	0.07
Inlet Mach Number		0.39
Compressor Exit Values		
Exit Temperature	(ºC)	138.88
Exit Pressure	(MPa)	4.75
Exit Blade Tip Speed	(m/s)	323.13
Exit He Density	(kg/m³)	5.24
Exit Tip Radius	(m)	0.22
Exit Blade Height	(m)	0.05
Exit Mach Number		0.33
Compressor Properties		
Number of Stages		8
Rotational Speed	(rpm)	13800
Compressor Length	(m)	0.52
Compressor Volume	(m³)	0.10
Compressor Dehaller Number		0.85
Axial Velocity	(m/s)	399.58
Mean Blade Speed	(m/s)	290.65
Mean Radius	(m)	0.20
Stage Temp. Increase	(ºC)	11.69
Total Temp. Increase	(ºC)	93.51
Aspect Ratio		3.00
First stage hub-tip ratio		0.70
First stage Tip Temp.	(ºC)	29.83
Swirl Angle	(degree)	6.00
Hade Angle	(degree)	2.02
Compressor Work	(MW)	79.15
HIGH PRESSURE COMPRESSOR		
Design Parameters		
Max. Blade Tip Speed	(m/s)	360.00
Polytropic Efficiency		0.90
Compressor Inlet Values		
Inlet Temperature	(ºC)	30.00
Inlet Pressure	(MPa)	4.73
Inlet Blade Tip Speed	(m/s)	343.48
Inlet He Density	(kg/m³)	7.13
Inlet Tip Radius	(m)	0.22
Inlet Blade Height	(m)	0.07

Inlet Mach Number		0.25
Compressor Exit Values		
Exit Temperature	(ºC)	128.53
Exit Pressure	(MPa)	8.50
Exit Blade Tip Speed	(m/s)	317.71
Exit He Density	(kg/m³)	9.95
Exit Tip Radius	(m)	0.20
Exit Blade Height	(m)	0.05
Exit Mach Number		0.22
Compressor Properties		
Number of Stages		8
Rotational Speed	(rpm)	15000
Compressor Length	(m)	0.47
Compressor Volume	(m³)	0.07
Compressor Dehaller Number		0.70
Axial Velocity	(m/s)	256.14
Mean Blade Speed	(m/s)	285.51
Mean Radius	(m)	0.18
Stage Temp. Increase	(ºC)	11.69
Total Temp. Increase	(ºC)	92.21
Aspect Ratio		3.00
First stage hub-tip ratio		0.70
First stage Tip Temp.	(ºC)	29.95
Swirl Angle	(degree)	5.00
Hade Angle	(degree)	1.99
Compressor Work	(MW)	71.63
HIGH PRESSURE TURBO TURBINE		
Design Parameters		
Max. Blade Tip Speed	(m/s)	360.00
Mechanical Efficiency		1.00
Polytropic Efficiency		0.90
Loss Coefficient		0.05
Stage Loading		1.80
Convergency Criteria		0.50
Rotational Speed	(rpm)	15000
Bypass Mass Flow	(kg/s)	7.00
Turbo Turbine Inlet Values		
Inlet Temperature	(ºC)	900.00
Inlet Pressure	(MPa)	8.32
Inlet He Density	(kg/m³)	3.42
Inlet Mach Number		0.17
Turbo Turbine Exit Values		
Exit Temperature	(ºC)	801.47
Exit Pressure	(MPa)	6.53
Exit He Density	(kg/m³)	2.93
Exit Mach Number		0.18
Turbo Turbine Properties		
Number of Stages		3

Turbo Turbine Length	(m)	0.46
Turbo Turbine Volume	(m^3)	0.07
Turbine Expansion Ratio		1.27
Turbine Loading		4.52
Turbine Actual Stage Loading		1.51
Turbine Reaction Ratio		0.30
Flow Coefficient		1.02
Axial Velocity	(m/s)	342.64
Mean Blade Speed	(m/s)	336.61
Mean Radius	(m)	0.21
Tip Blade Radius	(m)	0.26
Hub Radius	(m)	0.17
Hub-tip Radius Ratio		0.64
Stage Temp. Decrease	(ºC)	32.84
Total Temp. Decrease	(ºC)	98.53
Aspect Ratio		2.00
Rotor Inlet Gas Velocity	(m/s)	597.05
Rotor Inlet Temperature	(ºC)	876.98
Critical Pressure Ratio		2.05
NGV Exit Static Pressure	(MPa)	7.71
NGV Inlet Total Pressure	(MPa)	8.32
NGV exit He Density	(kg/m^3)	3.23
NGV Exit Fluid Flow Area	(m^2)	0.13
Turbine Work	(MW)	71.63
LOW PRESSURE TURBO TURBINE		
Design Parameters		
Max. Blade Tip Speed	(m/s)	360.00
Mechanical Efficiency		1.00
Polytropic Efficiency		0.90
Loss Coefficient		0.05
Stage Loading		1.80
Convergency Criteria		0.50
Rotational Speed	(rpm)	13800
Bypass Mass Flow	(kg/s)	6.65
Turbo Turbine Inlet Values		
Inlet Temperature	(ºC)	801.47
Inlet Pressure	(MPa)	6.54
Inlet He Density	(kg/m^3)	2.93
Inlet Mach Number		0.13
Turbo Turbine Exit Values		
Exit Temperature	(ºC)	686.86
Exit Pressure	(MPa)	4.78
Exit He Density	(kg/m^3)	2.40
Exit Mach Number		0.14
Turbo Turbine Properties		
Number of Stages		3
Turbo Turbine Length	(m)	0.62
Turbo Turbine Volume	(m^3)	0.11
Turbine Expansion Ratio		1.37
Turbine Loading		5.03

Turbine Actual Stage Loading		1.68
Turbine Reaction Ratio		0.55
Flow Coefficient		0.73
Axial Velocity	(m/s)	250.77
Mean Blade Speed	(m/s)	343.91
Mean Radius	(m)	0.24
Tip Blade Radius	(m)	0.30
Hub Radius	(m)	0.17
Hub-tip Radius Ratio		0.58
Stage Temp. Decrease	(ºC)	38.20
Total Temp. Decrease	(ºC)	114.61
Aspect Ratio		2.00
Rotor Inlet Gas Velocity	(m/s)	509.21
Rotor Inlet Temperature	(ºC)	782.56
Critical Pressure Ratio		2.05
NGV Exit Static Pressure	(MPa)	6.15
NGV Inlet Total Pressure	(MPa)	6.54
NGV exit He Density	(kg/m^3)	2.80
NGV Exit Fluid Flow Area	(m^2)	0.19
Turbine Work	(MW)	79.15
PRECOOLER		
Tube Arrangement Properties		
Total Number of Tubes		648
Tube Outer Diameter	(m)	0.0164
Tube Inner Diameter	(m)	0.0138
Pitch Length	(m)	0.0313
Fin Pitch	(per m)	275
Fin Thickness	(m)	0.0003
Hydraulic Diameter	(m)	0.0067
Radial Pitch	(m)	0.0343
Free Flow Area	(m^2)	0.4099
Free Flow Area / Frontal Area		0.4490
Heat Exchanger Properties		
Total Required Heat Transfer Area	(m^2)	5218.47
Required Cooler Length	(m)	4.25
Required Total Volume	(m^3)	19.40
Radial Length of the Annular Core	(m)	1.66
Working Fluid Properties		
Mass flow of Gas	(kg/m^2)	140.00
Mass flow of Water	(kg/m^2)	243.56
Reynolds Number of Gas		6325.79
Reynolds Number of Water		71603.26
Gas Side Total Pressure Drop	(Pa)	18301.15
Tube Side Total Pressure Drop	(Pa)	19097.88
INTERCOOLER		
Tube Arrangement Properties		
Total Number of Tubes		648
Tube Outer Diameter	(m)	0.0164
Tube Inner Diameter	(m)	0.0138
Pitch Length	(m)	0.0313

Fin Pitch	(per m)	275
Fin Thickness	(m)	0.0003
Hydraulic Diameter	(m)	0.0067
Radial Pitch	(m)	0.0343
Free Flow Area	(m^2)	0.3262
Free Flow Area / Frontal Area		0.4490
Heat Exchanger Properties		
Total Required Heat Transfer Area	(m^2)	4190.99
Required Cooler Length	(m)	3.50
Required Total Volume	(m^3)	15.58
Radial Length of the Annular Core	(m)	1.78
Working Fluid Properties		
Mass flow of Gas	(kg/m^2)	140.00
Mass flow of Water	(kg/m^2)	252.23
Reynolds Number of Gas		7949.66
Reynolds Number of Water		74151.64
Gas Side Total Pressure Drop	(Pa)	15736.11
Tube Side Total Pressure Drop	(Pa)	16720.78
	RECUPERATOR	
Geometry of the Box		
Angle	(degree)	85.00
Length	(m)	1.55
Height	(m)	0.43
Width	(m)	0.63
Support plate thickness	(mm)	10.00
Flow channel thickness	(mm)	10.82
Plate thickness	(mm)	1.00
Number of plates		98
Recuperator Effectiveness		0.98
BOX NUMBER 1		
Hot Side Inlet Temperature	(ºC)	508.92
Hot Side Inlet Pressure	(kPa)	2679.57
Hot Side Exit Temperature	(ºC)	446.23
Hot Side Exit Pressure	(kPa)	2679.38
Cold Side Exit Temperature	(ºC)	500.00
Cold Side Exit Pressure	(kPa)	8500.00
Cold Side Inlet Temperature	(ºC)	437.31
Cold Side Inlet Pressure	(kpa)	8500.81
Reynold Number for Hot Side		6597.09
Reynold Number for Cold Side		32378.14
Overall Heat Transfer Coefficient	(W/m^2K)	30200.66
BOX NUMBER 2		
Hot Side Inlet Temperature	(ºC)	446.23
Hot Side Inlet Pressure	(kPa)	2679.38
Hot Side Exit Temperature	(ºC)	383.69
Hot Side Exit Pressure	(kPa)	2679.20
Cold Side Exit Temperature	(ºC)	437.31
Cold Side Exit Pressure	(kPa)	8500.81
Cold Side Inlet Temperature	(ºC)	374.78

Cold Side Inlet Pressure	(kpa)	8501.60
Reynold Number for Hot Side		7003.84
Reynold Number for Cold Side		34400.25
Overall Heat Transfer Coefficient	(W/m²K)	30078.07
BOX NUMBER 3		
Hot Side Inlet Temperature	(ºC)	383.69
Hot Side Inlet Pressure	(kPa)	2679.20
Hot Side Exit Temperature	(ºC)	321.25
Hot Side Exit Pressure	(kPa)	2679.03
Cold Side Exit Temperature	(ºC)	374.78
Cold Side Exit Pressure	(kPa)	8501.60
Cold Side Inlet Temperature	(ºC)	312.34
Cold Side Inlet Pressure	(kpa)	8502.38
Reynold Number for Hot Side		7477.22
Reynold Number for Cold Side		36758.46
Overall Heat Transfer Coefficient	(W/m²K)	29939.84
BOX NUMBER 4		
Hot Side Inlet Temperature	(ºC)	321.25
Hot Side Inlet Pressure	(kPa)	2679.03
Hot Side Exit Temperature	(ºC)	259.02
Hot Side Exit Pressure	(kPa)	2678.87
Cold Side Exit Temperature	(ºC)	312.34
Cold Side Exit Pressure	(kPa)	8502.38
Cold Side Inlet Temperature	(ºC)	250.10
Cold Side Inlet Pressure	(kpa)	8503.16
Reynold Number for Hot Side		8036.30
Reynold Number for Cold Side		39550.43
Overall Heat Transfer Coefficient	(W/m²K)	29782.78
BOX NUMBER 5		
Hot Side Inlet Temperature	(ºC)	259.02
Hot Side Inlet Pressure	(kPa)	2678.87
Hot Side Exit Temperature	(ºC)	196.98
Hot Side Exit Pressure	(kPa)	2678.72
Cold Side Exit Temperature	(ºC)	250.10
Cold Side Exit Pressure	(kPa)	8503.16
Cold Side Inlet Temperature	(ºC)	188.06
Cold Side Inlet Pressure	(kpa)	8503.94
Reynold Number for Hot Side		8708.23
Reynold Number for Cold Side		42916.13
Overall Heat Transfer Coefficient	(W/m²K)	29602.69
BOX NUMBER 6		
Hot Side Inlet Temperature	(ºC)	196.98
Hot Side Inlet Pressure	(kPa)	2678.72
Hot Side Exit Temperature	(ºC)	135.14
Hot Side Exit Pressure	(kPa)	2678.57
Cold Side Exit Temperature	(ºC)	188.06
Cold Side Exit Pressure	(kPa)	8503.94
Cold Side Inlet Temperature	(ºC)	126.23
Cold Side Inlet Pressure	(kpa)	8504.72

Reynold Number for Hot Side		9534.34
Reynold Number for Cold Side		47069.97
Overall Heat Transfer Coefficient	(W/m²K)	29393.52
POWER TURBINE		
Design Parameters		
Mechanical Efficiency		1.00
Polytropic Efficiency		0.90
Loss Coefficient		0.05
Stage Loading		1.80
Rotational Speed	(rpm)	3000
Bypass Mass Flow	(kg/s)	6.32
Power Turbine Inlet Values		
Inlet Temperature	(ºC)	686.86
Inlet Pressure	(MPa)	4.79
Inlet He Density	(kg/m³)	2.40
Inlet Mach Number		0.07
Power Turbine Exit Values		
Exit Temperature	(ºC)	508.92
Exit Pressure	(MPa)	2.68
Exit He Density	(kg/m³)	1.65
Exit Mach Number		0.08
Power Turbine Properties		
Number of Stages		13
Power Turbine Length	(m)	1.76
Power Turbine Volume	(m³)	2.37
Turbine Expansion Ratio		1.79
Turbine Loading		22.00
Turbine Actual Stage Loading		0.44
Turbine Reaction Ratio		0.30
Flow Coefficient		0.62
Axial Velocity	(m/s)	127.63
Mean Blade Speed	(m/s)	205.85
Mean Radius	(m)	0.66
Tip Blade Radius	(m)	0.71
Hub Radius	(m)	0.60
Hub-tip Radius Ratio		0.86
Stage Temp. Decrease	(ºC)	13.81
Total Temp. Decrease	(ºC)	179.51
Aspect Ratio		2.00
Rotor Inlet Gas Velocity	(m/s)	228.37
Rotor Inlet Temperature	(ºC)	683.40
Critical Pressure Ratio		2.05
NGV Exit Static Pressure	(MPa)	4.73
NGV Inlet Total Pressure	(MPa)	4.79
NGV exit He Density	(kg/m³)	2.38
NGV Exit Fluid Flow Area	(m²)	0.42
Power	(MW)	116.74

References

[1] “Review of the Pebble Bed Modular Reactor (PBMR) Plant" Current Status and Future Development of Modular High Temperature Gas Cooled Reactor Technology, p.21, IAEA-TECDOC-1198, 2000.

[2] Introduction to the Pebble Bed Modular Reactor (PBMR), Document No: 009949-185, Rev.1, p.43-49, 2001