Available online at www.sciencedirect.com
ScienceDirect
Fusion Engineering and Design 82 (2007) 2689–2695
Fusion Engineering and Design
www.elsevier.com/locate/fusengdes

Power conversion cycles study for He-cooled reactor concepts for DEMO

M. Medrano [a,*], D. Puente [b], E. Arenaza [b], B. Herrazti [b], A. Paule [b], B. Brañas [a], A. Orden [b], M. Domínguez [b], R. Stainsby [c], D. Maisonnier [d], P. Sardain [d]

[a] *EURATOM-CIEMAT Association for Fusion, Avda. Complutense, 22, Madrid 28040, Spain*
[b] *IBERTEF Magallanes 22, Madrid 28015, Spain*
[c] *AMEC-NNC, Booths Hall, Chelford Road, Knutsford, Cheshire WA16 8QZ, UK*
[d] *EFDA-Close Support Unit Garching, Boltzmannstrasse 2, D-85748 Garching, Germany*

Received 31 July 2006; received in revised form 25 April 2007; accepted 25 April 2007
Available online 12 June 2007

Abstract

The study of different power conversion cycles have been performed in the framework of the DEMO scoping studies to provide technical information focused on the selection of DEMO parameters. The purpose of this study has been the investigation of "advanced cycles" in order to get an improvement on the thermodynamic efficiency. Starting from the "near term" He-cooled blanket concepts (HCLL, HCPB), developed within the Power Plant Conceptual Studies (PPCS) and currently considered for DEMO, conversion cycles based on a standard Rankine cycle were shown to yield net efficiencies (net power/thermal power) of approximately 28%. Two main features limit these efficiencies. Firstly, the heat sources in the reactor: the blanket which provides over 80% of the total thermal power, only produces moderate coolant temperatures (300–500 °C). The remaining thermal power is deposited in the divertor with a more respectable coolant temperature (540–717 °C). Secondly, the low inlet temperature of blanket coolant limits the possibilities to achieve efficient heat exchange with cycle. The parameters of HCLL model AB have been used for the analysis of the following cycles: (a) supercritical steam Rankine, (b) supercritical CO_2 indirect Brayton and (c) separate cycles: independent cycles for the blanket and divertor.

A comparison of the gross and net efficiencies obtained from these alternative cycles alongside the standard superheated Rankine cycle will be discussed in the paper.

Keywords: Power plants; Supercritical cycles; DEMO

1. Introduction

In the framework of the DEMO Conceptual Study, a series of scoping studies have been launched with

* Corresponding author. Tel.: +34 91 3466639; fax: +34 91 3466124.
E-mail address: mercedes.medrano@ciemat.es (M. Medrano).

0920-3796/$ – see front matter © 2007 Elsevier B.V. All rights reserved.
doi:10.1016/j.fusengdes.2007.04.041

the aim of providing technical information focused on the selection of DEMO parameters. After the completion of these studies the proper design activities on DEMO will be followed. The ultimate goal of DEMO is to demonstrate the technological viability of the fusion power (electricity production). Following previous results of the Power Plant Conceptual Studies (PPCS) [1] the helium-cooled blanket concepts (named HCLL, HCPB) as well as the DCLL (dual coolant, LiPb/He) concept, are the ones currently considered for DEMO. For these plant models a He-cooled divertor design was investigated as well. The implementation of a He-cooled reactor (blanket and divertor) is considered essential for a DEMO Conceptual Study. The conversion cycles considered for these models in the PPCS phase were standard Rankine.

In the present study, the helium-cooled lithium lead (HCLL) model AB has been selected for the analysis of different advanced power conversion cycles, with the aim of improving the thermodynamic efficiency with respect to the one obtained for the standard Rankine. For this purpose, the primary circuit of the HCLL has been coupled to supercritical (SC) cycles, such as SC Rankine and SC CO_2 indirect Brayton. A comparison of the gross/net efficiencies obtained for the different cases alongside the standard superheated Rankine will be discussed in the paper.

2. Primary heat transport system (PHTS) parameters for the HCLL model AB

The PHTS parameters [2] defined for this model within the PPCS phase and used for the current calculations are summarized in Table 1. Two heat sources are present in the reactor: the blanket that provides 82% of the total thermal power with a moderate coolant temperature (300–500 °C) and the divertor, with a more respectable coolant temperature (540–717 °C) delivers 18% of the thermal power. The latter is considered a high-grade heat source. Additionally, the helium blowers raise the coolant temperature: on the one hand this increases the thermal energy available in the helium, on the other, it forces the helium outlet temperature in the blanket heat exchanger (HEx) to be accordingly, lower than 300 °C (see Section 3; Fig. 1). These features of the heat sources together with the low inlet temperature of the blanket coolant, limit the gross efficiency obtained with the cycle as it will be discussed in the paper.

Table 1
PHTS parameters for HCLL model AB

Parameters	HCLL model AB
Fusion power (MW)	4290
Thermal power to PHTS (MW)	5145
Total thermal power (MW)	5509
Blanket	
Thermal power from blanket (MW)	4218.76
Thermal power from blowers (MW)	273
Helium flow (kg/s)	4070
Coolant temperature, inlet/outlet to HEX (°C)	500/287
Divertor	
Thermal power from divertor (MW)	926.07
Thermal power from blowers (MW)	91
Helium flow (kg/s)	1010
Coolant temperature, inlet/outlet to HEX (°C)	717/522

The PHTS layout considered for the HCLL model AB consisted of nine cooling loops for the blanket and three for the divertor. The heated helium in the blanket loops is conducted to nine steam generators (one per loop) and the divertor coolant loops transfer the heat to three steam superheaters. A superheat and regenerative Rankine cycle coupled to the PHTS resulted in a gross power of 2353 MW, with a gross efficiency (gross power/thermal power) of 45.74%, and a net efficiency (net power/thermal power) of 28.34%. In this configuration, the steam enters the HP section of the turbine at a temperature of 642 °C and 8.6 MPa. The investigation of more efficient cycles is presented in the next sections.

3. Supercritical Rankine cycles

In order to explore an improvement of the thermal efficiency supercritical Rankine cycles have been studied firstly. Dramatic improvements in power plant performance can be achieved by raising inlet steam conditions (P, T). They also constitute highly regenerative cycles as the external thermal sources are at very high temperature.

On the contrary, high pressure implies more pumping power, fact that is compensated by the bigger power density in the steam.

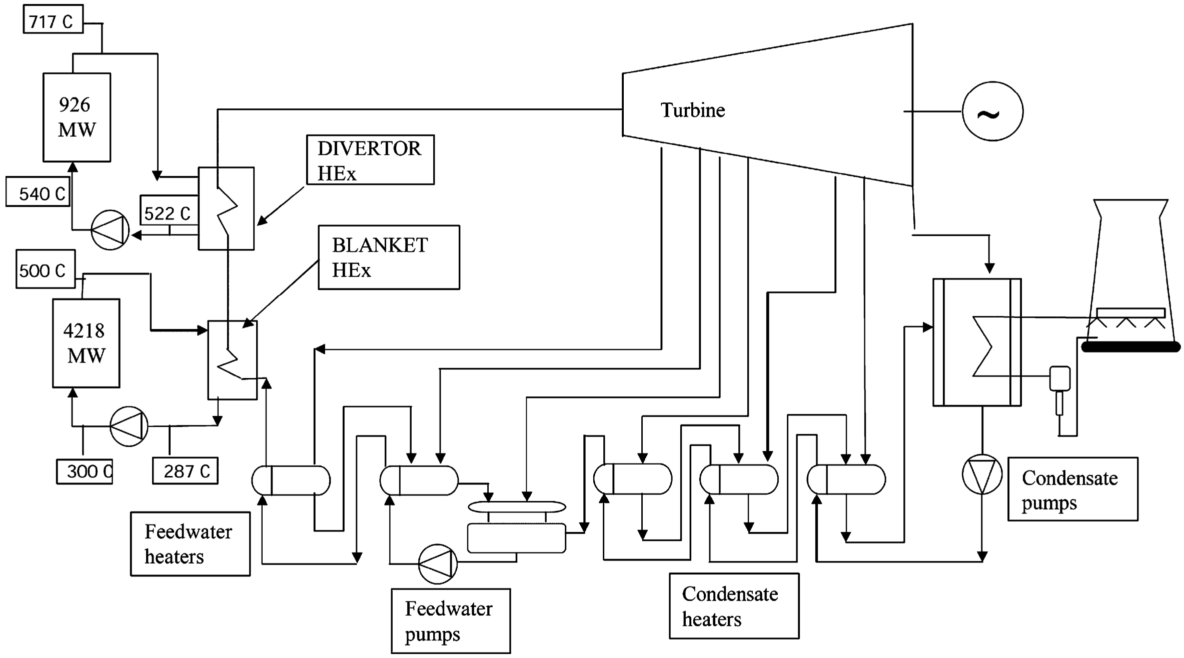

Fig. 1. Superheat cycle flow diagram.

The study of several SC configurations has been performed using the commercial computing software THERMOFLEX, Version 15. In all the cases, the steam pressure values are above 28 MPa (critical parameters for water: 374 °C, 22.1 MPa). Turbine isentropic efficiency of 87% and electromechanical efficiency of 98.5% have been considered. Pressure and thermal losses have been taken into account for the components. A pinch temperature of 10 °C has been considered for the HEx's (He/SC steam). A summary of the analysed cycles is presented next and the results of the calculations are included in Table 2.

3.1. Superheat cycle

Steam generation is produced in the blanket HEx and it is further superheated in the divertor HEx, entering the HP turbine at a temperature of 530 °C. Part of

Table 2
Results of the SC cycles alongside the standard Rankine

	SC superheat cycle	SC reheat cycle	SC improved cycle	Standard Rankine cycle
Thermal input (MW)	5144.83	5144.83	5144.83	5144.83
HP inlet temperature (°C)	530.8	456.7	525.4	642.5
LP inlet temperature (°C)	–	433	556.4	346.2
HP inlet pressure (bar)	280	280	280	86
LP inlet pressure (bar)	–	70	70	12
Steam mass flow (kg/s)	2400	2200	1800	3737
Gross power (MW)	2433.8	2400.96	2566.23	2353.3
Feedwater pump power (MW)	113.032	102.959	86.147	42.84
Condensate pump power (MW)	3.778	3.468	2.176	4.907
Other auxiliaries (MW)	847.43	847.43	847.43	847.43
Net power (MW)	1469.56	1447.10	1629.99	1458.23
Cycle gross efficiency (%)	47.31	46.67	49.88	45.74
Cycle net efficiency (%)	28.56	28.13	31.68	28.34

the steam thermal energy is used for preheating the feedwater by means of seven extractions from the turbine. A net efficiency of 28.56% is obtained for this case.

The flow diagram corresponding to the superheat cycle is shown in Fig. 1.

3.2. Reheat cycle

The blanket heat is used for steam generation and a slight superheating, whereas the divertor heat is used either for further heating of the steam or to reheat the steam expanded in the HP turbine. Different ratios of the divertor thermal power devoted to superheating/reheating have been analysed concluding that the use of the whole divertor thermal power for superheating shows higher efficiency (this extreme case is the one analysed in Section 3.1). The opposite case in which the divertor thermal power is entirely used for reheating, drive to HP and LP turbine inlet temperatures of 456 and 433 °C. The gross and net efficiencies obtained present a decrease of 0.64 and 0.43 percentage points, respectively, compared to the superheat case (see Table 2). The thermal transfer effectiveness in the divertor HEx is poorer for this case than for the superheat case.

3.3. Improved cycle

This cycle aims at optimizing the thermal exchange between primary and secondary circuits attempting a new PHTS configuration. The optimum configuration is obtained by the split of the blanket HEx units into two stages with a parallel HEx layout. A total of 18 HEx (9×2) for the 9 blanket loops are proposed while 3 HEx are maintained for the divertor loops. The following arrangement has been considered: for the blanket, nine HEx (first stage) are devoted to steam generation, seven HEx (second stage) are used for steam generation + superheating and two HEx (second stage) are used to reheat. For the divertor, two HEx are used for superheating and one HEx is used for reheating. This configuration leads to closer heat transfer curves between the primary and secondary, maximizing the thermal exchange effectiveness. It results in higher steam temperatures (increase of gross efficiency) and less steam mass flow (increase of net efficiency) compared to the other SC cycles.

The SC superheat and reheat cycles present higher gross efficiencies and similar net efficiencies compared to the standard Rankine. The "improved" cycle presents the best values of all the cases showing respect to the standard Rankine, an increase in gross and net efficiencies more than 4 and 3 percentage points, respectively.

However, the more complex layout considered in this case, required a review of the primary pressure losses. A rough estimation showed a 10% higher He pumping power and a decrease up to 0.7% of the net efficiency respect to the value shown in Table 2.

4. Supercritical CO_2 indirect Brayton cycles

The interest for the SC CO_2 is its potential for high efficiency at low temperatures due to the low compression work near the critical point (7.38 MPa, 31 °C). A first approach to SC CO_2 Brayton cycles that could fit best to the particular characteristics of the HCLL has been carried out. The calculations have been performed using a CO_2 cycle model developed by Ibertef. Results have been checked by an independent model developed by AMEC-NNC with good agreement between them.

As starting point, a simple recuperated cycle with a single compression stage has been considered as "base cycle". Preliminary calculations for this case point out a very low efficiency compared to the fission reactors with a similar configuration. The main reason is the low outlet temperature of helium in the blanket HEx (287 °C) that requires a maximum CO_2 inlet temperature of 262 °C. This fact limits the amount of thermal energy that can be recovered in the recuperators and the use of an auxiliary compressor. The efficiency is also limited by the relative low temperature of the helium blanket at 500 °C and the small quantity of high-grade heat from the divertor; all this results in a turbine inlet temperature up to 525 °C for the CO_2, which is a low value for a gas cycle. Other options have been studied in order to improve the efficiency obtained for the base cycle: a reheat cycle, a single cycle with multistage compression and intercooling and a recompression cycle. The latter yielded the better option, and a detailed calculation for this cycle was performed as it is presented next.

Table 3
Input parameters for the recompression cycle

Maximum/minimum cycle pressure (bar)	200/74
Minimum CO_2 temperature (°C)	30
Turbine/compressors isentropic efficiency (%)	93/95
Electromechanical efficiency (%)	98
Recuperators effectiveness (%)	95
Pressure loss in the HTR and LTR (both sides) (bar)	0.5
Pressure loss HEx's (CO_2 side) (bar)	2

4.1. Recompression cycle

This cycle [3] improves the efficiency by reducing the heat rejection from the cycle introducing an auxiliary compressor, bypassing the main cooler, the main compressor and the low temperature recuperator. A reduced compression work is obtained taking advantage of the CO_2 inlet conditions close to the critical point at the main compressor, as well as the improvement of the performance of the recuperators by feeding to the auxiliary compressor with a certain flow fraction (which has to be optimized).

Fig. 2 shows the flow diagram of the recompression cycle considered for this case, with the secondary side of the HEx's of the blanket and divertor connected in series. The input parameters for the calculations are included in Table 3. The maximum temperature at the turbine inlet was set to 400.7 °C and the optimum recompression fraction was 0.41. Pressure losses in the components have been taken into account (based on GCFR studies) nevertheless the losses due to cooling loops have not been evaluated within this study.

The results of this configuration are presented in Table 5. A net efficiency of 26.01% is obtained in this case (lower than any of the Rankine options). The conclusion is that the thermal power from the blanket and divertor integrated into a sole recompression cycle, conducts to a non-optimal use of the available divertor exergy. For this reason, the combination of two independent cycles for the blanket and the divertor is assessed in the next section.

5. Separate cycles for blanket and divertor

The previous calculations pointed out that the low temperature in the helium coolant blanket loops makes the Brayton cycle gross efficiency low compared to the results obtained for the "improved" SC Rankine. However, a SC CO_2 Brayton devoted to use the divertor thermal energy would result much better from the heat exchange point of view. In order to explore the optimization of both heat sources independently, the following options have been considered.

5.1. Standard Rankine for the blanket + SC CO_2 Brayton for the divertor

A Rankine cycle with steam parameters in the HEx's outlet of 480 °C/9 MPa, has been selected for the blanket. Since it is not a high temperature source, neither a reheat cycle nor supercritical pressures has been chosen.

A SC CO_2 recompression cycle devoted to the divertor has the objective of getting a more efficiency heat exchange in the HEx (He/CO_2), as well as to attain a higher turbine inlet temperature. The input parameters for the calculations are those presented in Table 3. The results of the combined cycle are shown in Table 5.

5.2. Independent SC CO2 Brayton for the blanket and the divertor

In this proposal two SC CO_2 recompression independent cycles for blanket and divertor are studied (Dual cycles). This solution has derived as the most convenient because more efficiency can be gained if the two sources cycles work at different pressure range. For this reason, the two separate cycles have no common cycle components with the exception of a single turbomachine shaft and generator. The input parameters used for this calculation are presented in Table 4. Maximum pressure in the blanket cycle has been increased

Table 4
Input parameters for the cycle 5.2

	Blanket	Divertor
P_{min}, P_{max} (bar)	75/251	75/201
T_{min}, T_{max} (°C)	30/440	30/680
Recompression fraction (optimum)	0.37	0.38
Turbine/compressors isentropic efficiencies	0.93/0.95	0.93/0.95
Recuperators effectiveness	0.95	0.95
Electromechanical efficiency	0.98	0.98
Pressure losses in the HTR and LTR (bar)	0.5	0.5
Pressure loss in HEx (CO_2 side) (bar)	2	2

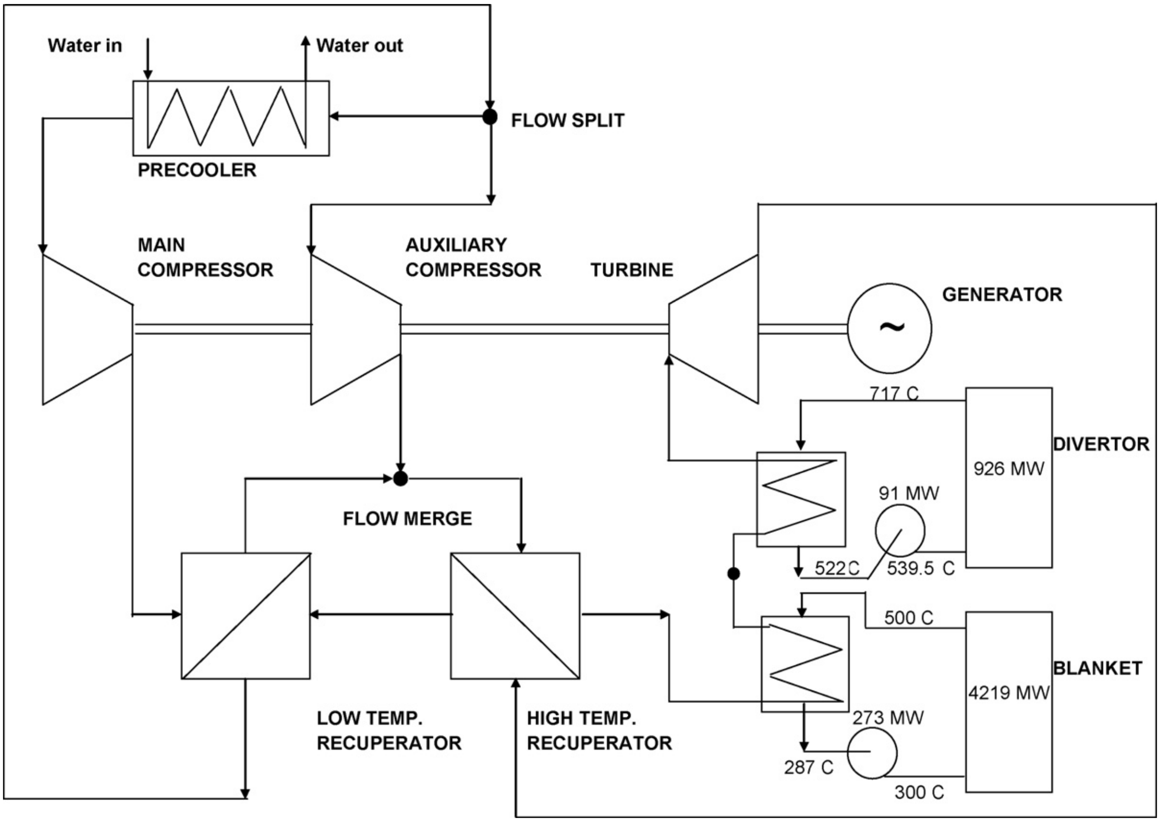

Fig. 2. Flow diagram for the recompression cycle.

up to 250 bar with maximum temperature at the turbine inlet set to 440 °C. In the divertor cycle instead, 200 bar maximum pressure has been maintained in order to preserve the integrity of the HEx working at higher temperatures of 680 °C. Likewise in the case of the blanket and divertor integrated into a sole recompression cycle, pressure losses in the components have been taken into account although the losses due to cooling loops have

Table 5
Results of the most relevant cycles analysed

	SC CO_2 Brayton recompress	Independent cycles: Rankine/SC CO_2	Independent cycles: SC CO_2/SC CO_2	SC Rankine improved cycle	Rankine standard
Fusion power (MW)	4290	4290	4290	4290	4290
Thermal power (MW)	5144	5144	5144	5144	5144
Blanket	4219	4219	4219	4219	4219
Divertor	926	926	926	926	926
Divertor gross power (MW)	–	531	527	–	–
Blanket gross power (MW)	–	1747	1928	–	–
Helium compressors (MW)	370	370	370	370	370
Auxiliary heating (MW)	477	477	477	477	477
Water pumps (MW)	–	40	–	88.32	47
Total gross power (MW)	2185	2278	2455	2566	2353
Total net power (MW)	1338	1390	1608	1629	1458
Cycle gross efficiency (%)	**42.49**	**44.29**	**47.73**	**49.88**	**45.74**
Cycle net efficiency (%)	**26.01**	**27.04**	**31.26**	**31.68**	**28.34**

Bold data are the final results of the study performed.

not been evaluated in the study. The calculation results are included in Table 5.

6. Conclusions

1. Different SC (Rankine, CO_2) conversion cycles have been analysed for HCLL model AB with the objective of improving the thermodynamic efficiency with respect to the standard Rankine studied within the PPCS phase.
2. The results of the most relevant cycle analysed can be compared in Table 5.
3. The SC Rankine leads to the highest gross and net efficiencies for the best cycle option ("improved case").
4. The SC CO_2 recompression (blanket and divertor integrated into a sole recompression cycle) achieves low efficiencies due to the particular characteristics of the thermal power available at the reactor.
5. Among all cycle configurations analysed based on SC CO_2, the dual recompression cycles for the blanket and divertor yield net efficiencies comparable to the "improved" SC Rankine.
6. The improvement in the net efficiency compared to the standard Rankine (PPCS phase) is up to 3.34 and 2.92 percentage points for the SC Rankine and SC CO_2 dual recompression, respectively.
7. It should be mentioned that reactor design modifications allowing higher coolant temperatures would increase the achievable efficiencies for all cycle configurations. Particularly the increase in the required coolant temperature at blanket inlet, which for HCLL was limited to 300 °C, would lead to noticeable efficiency gains of the recompression CO_2 cycles.

Acknowledgements

This work has been supported by the European Communities under the contract of Association EURATOM-CIEMAT and carried out within the framework of the European Fusion Development Agreement (EFDA). The views and opinions expressed in this paper do not necessarily reflect those of the European Commission.

References

[1] D. Maisonnier, I. Cook, P. Sardain, L. Boccaccini, E. Bogusch, K. Broden, L. Di Pace, R. Forrest, L. Giancarli, S. Hermsmeyer, C. Nardi, P. Norajitra, A. Pizzuto, N. Taylor, D. Ward, The European power plant conceptual study, in: Proceedings of the 23rd Symposium of Fusion Technology—SOFT 23, Fusion Eng. Design 75–79 (November) (2005) 1173–1179.

[2] A. Li Puma, J.L. Berton, B. Brañas, L. Bühler, J. Doncel, U. Fischer, W. Farabolini, L. Giancarli, D. Maisonnier, P. Pereslavtsev, S. Raboin, J.-F. Salavy, P. Sardain, J. Szczepanski, D. Ward, Breeding blanket design and systems integration for a helium-cooled lithium–lead fusion power plant, in: Proceedings of the Seventh International Symposium on Fusion Nuclear Technology—ISFNT-7 Part A, Fusion Eng. Design 81 (February (1–7)) (2006) 469–476.

[3] V. Dostal, P. Hejzlar, M.J. Driscoll, N.E. Todreas, A supercritical CO_2 Brayton cycle for next generation reactors, in: Proceedings of ICONE-10, Arlington, Virginia, April 14–18, 2002.