Proceedings of the 2nd IAEA Technical Meeting on First Generation of Fusion Power Plants: Design & Technology

Alternative power conversion cycles for He-cooled fusion reactor concepts

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Abstract

The He-cooled PPCS concepts using helium at 300 °C – 500 °C have power conversion systems using standard Rankine cycles. Their gross efficiency is mainly limited by the moderate He output temperature whilst the net efficiency (net power/fusion power) is relatively low due to the high power required by the auxiliaries, mainly pumping and heating. Possible improvements of the gross efficiency have been investigated, considering other types of conversion cycles: the indirect Brayton cycle using supercritical CO_2 as working fluid and the supercritical steam Rankine cycle.
The CO_2 has interesting physical properties (critical temperature near room temperature, moderate value of critical pressure, stability under 1400°C) and low intrinsic costs. Moreover, due to its sizeable molecular weight, CO_2 needs small turbines, compared to He and steam turbines. The supercritical steam Rankine cycle are already used in coal-fired power plants, so that the turbine technology can be considered mature.
Among all configurations analyzed, the one leading to the highest efficiencies corresponds to a supercritical Rankine, in which the heat transfer is improved dividing the blanket helium heat exchange in two stages. At the first stage the heat exchangers are used for steam generation only whilst at the second stage they are also used for superheating and reheating. The value obtained for the so-called "Cycle related Net Efficiency" (net power/reactor thermal power), 31.68%, represents a noticeable improvement compared to the one obtained for the sub-critical Rankine cycle of the reference PPCS model HCLL (Helium Cooled Lithium-Lead), which achieved a value for this ratio of 28.34%. A supercritical Rankine cycle with these characteristics represents nowadays a relatively mature technology, and investment cost should not rise considerably compared to those of a sub-critical Rankine cycle.

1. Introduction

A Power Plant Conceptual Study (PPCS) has been carried out in Europe between 2001 and 2004, which aimed at the demonstration of the credibility, the safety and environmental advantages and the economic viability of fusion power [1]. In this framework, three "near term" reactors models have been studied, which were based on limited extrapolation on both physics and technology. Among them, two reactor models were He-cooled, the helium Cooled Lithium Lead (HCLL) and the Helium Cooled Pebble Bed (HCPB) concpts. For these plant models a He-cooled divertor design was investigated as well. The conversion cycles considered for these models in the PPCS phase were standard Rankine. Their gross efficiency is limited by the moderate He output temperature (300 – 500 ºC in the blankets). A study has been launched in order to investigate possible improvements of the gross efficiency by using other types of conversion cycles: the indirect Brayton cycle using supercritical CO_2 as working fluid and the supercritical steam Rankine cycle. In the study, the HCLL concept [2] (named model AB in the PPCS) has been selected for the analysis of these advanced power conversion cycles. A comparison of the efficiencies obtained for the different cases with the standard superheated Rankine is made.

2. Primary Heat Transport System (PHTS) parameters for the HCLL concept

The PHTS parameters 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 (300-500º C) and the divertor, with a more respectable coolant temperature (540-717º C) delivers 18 % of the thermal power. The latter is 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 hand it forces the helium outlet temperature in the blanket heat exchanger (HEx) to be accordingly, lower than 300º C (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.
The PHTS layout considered for the HCLL model AB consisted of 9 cooling loops for the blanket and 3 for the divertor. The heated helium in the blanket loops is conducted to 9 steam generators (one per loop) and the divertor coolant loops transfer the heat to 3 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 / total thermal power) of 45.74%, and a net efficiency (net power/total thermal power) of 28.34%. In this configuration the steam enters the HP section of the turbine at a temperature of 642º C and 8.6 MPa. The investigation of more efficient cycles is presented in the next sections.

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 (º 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 (º C)	717/522

Table 1: PHTS parameters for HCLL Model AB

3. Supercritical Rankine cycles

In order to explore an improvement of the thermal efficiency supercritical (SC) 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.
The study of several SC configurations has been performed, considering in all cases steam pressure values above 28 MPa (critical parameters for water: 374º C, 22.1 MPa), turbine isentropic efficiency of 87 % and electromechanical efficiency of 98.5%. Pressure and thermal losses have been taken into account for the components. A pinch temperature of 10ºC 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 530º C. Part of 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.

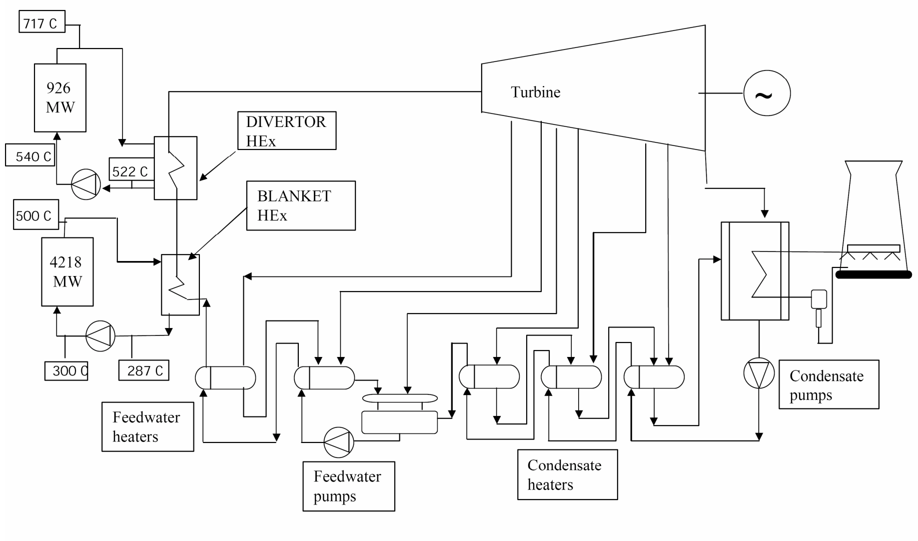

Fig. 1: Superheat cycle flow diagram

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 analyzed in 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 456º C and 433º C. The gross and net efficiencies obtained are respectively 1.3 and 1.5 % lower than for 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 x 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, 9 HEx (first stage) are devoted to steam generation, 7 HEx (second stage) are used for steam generation + superheating & 2 HEx (second stage) are used to reheat. For the divertor, 2 HEx are used for superheating and 1 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.

	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 (ºC)	530.8	456.7	525.4	642.5
LP inlet temperature (ºC)	--	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**	**2566.233**	**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	847.92	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

Table 2: Results of the SC cycles alongside the standard Rankine

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 over 8 % and 10 % 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, 31º 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. 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 (287º C) that requires a maximum CO_2 inlet temperature of 262º 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 500ºC and the small quantity of high-grade heat from the divertor; all this results in a turbine inlet temperature up to 525º 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 inter-cooling and a recompression cycle. The latter yielded the better option, and a detailed calculation for this cycle was performed as it is presented next.
Recompression cycle: This cycle 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 compressor. The flow diagram corresponding to this cycle is shown in Fig. 4.
The input parameters for the calculations are included in Table 3 and the corresponding results are presented in Table 4.

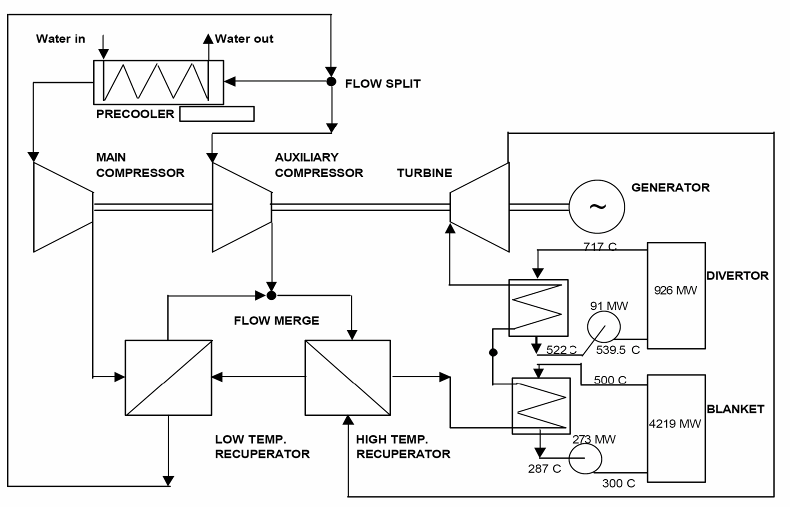

Fig. 4: Flow diagram for the Recompression cycle

Maximum cycle pressure	200bar
Minimum cycle pressure	75 bar
Minimum CO_2 temperature	30 C
Turbine isentropic efficiency	93%
Compressor isentropic efficiency	95%
Electromechanical efficiency	98%
Recuperators effectiveness	95%
Pressure loss in the HTR&LTR (both sides)	0.5 bar
Pressure loss HEx´s (CO2 side)	< 2 bar

Table 3: Input parameters for the recompression cycle

Recompression Cycle	
Thermal output to PHTS (MW)	5144.83
Gross power (MW)	2185.48
Blanket helium compressor consumption (MW)	278
Divertor helium compressor consumption (MW)	92
Other auxiliaries (MW)	477.29
Net Power (MW)	1338.19
Cycle Gross Efficiency (%)	42.84
Cycle Net Efficiency(%)	26.01

Table 4: Results of the recompression cycle

A net efficiency of 23.01 % 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 used 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 & 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 of 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 Brayton devoted to the divertor has the objective of getting a more efficiency heat exchange in the HEx (He/CO2), 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 6.

5.2 <u>Independent SC CO_2 Brayton for the blanket and the divertor:</u> In this proposal two SC CO_2 independent circuits for blanket and divertor are studied. This solution has derived as the most convenient because more efficiency can be gained if the two sources cycles work at different pressure range. The parameters used for this calculation are presented in Table 5 and the results included in Table 6.

	Blanket	Divertor
Pmin, Pmax. (bar)	75 / 250	75 /200
Tmin, Tmax (° C)	30 /440	30 /680
Recompression fraction (optimum)	0.37	0.38
Recuperators effectiveness	0.95	0.95
Compressors isentropic efficiencies	0.95	0.95
Turbine isentropic efficiency	0.93	0.93
Pressure losses in the HTR&LTR	0.5	0.5
Pressure loss in HEx (CO2 side)		

Table 5: Input parameters for the cycle 5.2

6. Conclusions

The results of the most relevant cycle analyzed can be compared in Table 6.

	SC CO2 Brayton recompression	SC Rankine "improved"	<u>Separate cycles:</u> Rankine/ SC CO_2	<u>Separate cycles:</u> SC CO_2 / SC CO_2	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	546	---
Blanket Gross Power (MW)	---	---	1747	2000	---
Helium compressors (MW)	370	370	370	370	370
Auxiliary heating (MW)	477	477	477	477	477
Water pumps (MW)	---	88.32	40	---	47
Total Gross Power (MW)	2185	2566	2278	2547	2353
Total Net Power (MW)	1338	1629	1390	1701	1458
Cycle Gross Efficiency (%)	**42.49**	**49.88**	**44.29**	**49.51**	**45.74**
Cycle Net Efficiency (%)	**26.01**	**31.68**	**27.04**	**33.07**	**28.34**

Cycle gross efficiency = gross electrical output /thermal power
Cycle net efficiency = net electrical output / thermal power

Table 6: Results of the most relevant cycles analyzed

The recompression CO2 supercritical cycle achieves low efficiencies due to the particular characteristics of the thermal power available at the reactor.
The use of separate cycles for Divertor and Blanket (CO2 supercritical cycle and Rankine cycle respectively) leads to a significant efficiency gain.
Among all configurations analyzed, the one leading to the higher efficiencies corresponds to the supercritical Rankine. The value obtained for the so-called "Cycle related Net Efficiency" (Net Power/Reactor Thermal Power), 31.68%, represents a noticeable improvement compared to the one obtained for the sub-critical Rankine cycle of the reference model AB, which achieved a value for this ratio of 28.34%. A supercritical Rankine cycle of these

characteristics represents a nowadays relatively mature technology, and investment cost should not rise considerably compared to those of a sub-critical Rankine cycle.

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 model AB was limited to 300ºC, 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.

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