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D1.1 – sCO2 Brayton cycle architecture and components' specifications

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WP 1, T 1.1

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sCO2-Flex

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Technical References

Project Acronym	sCO2-Flex
Project Title	Supercritical CO2 Cycle for Flexible and Sustainable Support to the Electricity System
Project Coordination	Albannie Cagnac sCO2-flex Project Coordinator Email: albannie.cagnac-1@edf.fr Tel: +33 (0)1 30 87 86 64
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[1] PU = Public

PP = Restricted to other programme participants (including the Commission Services)

RE = Restricted to a group specified by the consortium (including the Commission Services)

CO = Confidential, only for members of the consortium (including the Commission Services)

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Document history

V	Date	Beneficiary	Author
1	2018/04/04	EDF	Mounir MECHERI
2	2018/04/27	All	Partner leaders
3.1	2018/04/27	EDF	Albannie CAGNAC
3.2			

Summary

This deliverable summarizes the simulation results of the task 1.1 entitled "sCO_2 Brayton cycle architecture and components' specifications". The aim of this document is to analyse the behaviour (performance assessment, components' specifications) of a "pre-selected list" of cycle architecture with the process modelling software AspenPlus® to identify the most interesting architectures that fit the project constraints (high performances, simplicity for control stability, moderate boiler inlet temperature…).

More than 40 sCO_2 Brayton cycle architectures can be found in the literature but chosen cycle for the sCO_2-Flex project must fit coal boiler constraints (such as low temperature of the working fluid at the boiler inlet, low pressure drops for high flow rate, good heat integration for a high boiler efficiency…), be efficient and suitable for flexible operation loads.

This document analyses "Recompression", Partial cooling", Pre-compression", "Turbine split flow", "Preheating" and "Split-expansion" cycle configurations.

Assumptions and hypotheses required to perform these thermodynamic simulations are detailed in the document.

The obtain results enables to assess the global performances of the studied cases (cycle net efficiency, boiler efficiency…) as well as the global heat and mass balance table.

The results of this deliverable will be used as "inlet data" for the deliverable D1.3.

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Disclaimer

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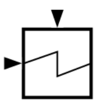
Nomenclature

Symbol	Description	Unit
sCO_2	Supercritical CO_2	-
WP	Work package(s)	-
T	Temperature	°C
P	Pressure	MPa
D	Heat duty	MWth
E	Electrical power	MWe
M	CO_2 Mass flow	kg/s
EFF	Efficiency	%
HTR	High temperature recuperator	-
LTR	Low temperature recuperator	-
H. Ex	Heat Exchanger(s)	-
XX	Double digit number	-

Acronym	Partner
POLIMI	Politecnico di Milano
BHGE	Baker Hughes General Electric
EDF	Electricité de France

Symbol	Type	Labelling
	Heat sinks	MSCUSXX
	Heat sources (heaters)	MSHSOXX
	Compressor	MSCOMXX
	Turbine	MSTURXX
 or 	Recuperator	MSRCUXX

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Context

The global objective of the sCO_2-Flex European project is to design a 25 MWe Brayton cycle working with supercritical CO_2 (sCO_2). The cycle architecture is not fixed at the beginning of the project and many configuration options can be considered. Because it is not possible to design the cycle components for all these configurations (time-consuming), the project must focus on one cycle (the most convenient cycle that fit the project framework) among the several available configurations, without taking the risk of precluding the best cycle layout. Thus, preliminary to this selection, a global screening and performance assessment of the most interesting cycle architectures regarding the project framework must be done to have a better knowledge about the cycle configuration specificities and the components main parameters in these configurations (for cycle comparison and selection). This "cycle architecture" screening method is based on a sensibility analysis and is not a complete cycle optimization.

The results of this deliverable will be used as "inlet data" for the deliverable D1.3.

Objectives

The main objective of this study is to analyse the behaviour (performance assessment, components' specifications) of a "pre-selected list" of cycle architecture with the process modelling software AspenPlus® to identify the most interesting architectures that fit the project constraints (high performances, simplicity for control stability, moderate boiler inlet temperature…). This step is built on the knowledge given by previous simulation experiences [Le Moullec, 2013; Mecheri & Le Moullec, 2016] and literature review [Angelino, 1968; Crespi, 2017] that explain why some configurations are expected to offer best performances or lowest "boiler inlet temperature" than other architectures.

All process flow diagram and global heat and mass balance of studied architectures are given in appendix.

The sCO_2 Brayton cycle is very sensitive to assumptions made such as the cycle pressure drop values, the cycle maximum acceptable temperature and pressure and the cooling temperature [Dostal, 2004; Mecheri & Le Moullec, 2016]. Before analysing the cycle architectures, a "sensibility analysis" regarding the cited parameters is done in this document to stress out the importance of the chosen assumption on the obtained results.

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Methodology

More than 40 sCO_2 Brayton cycle architectures can be found in the literature [Crespi et al, 2017], but not all of them are compatible with the project framework. Indeed, the chosen cycle must fit coal boiler constraints (such as low temperature of the working fluid at the boiler inlet, low pressure drops for high flow rate, good heat integration for a high boiler efficiency…), be efficient and suitable for flexible operation loads.

In this context, this study is split in two parts:

- First: the implementation of the sensibility analysis done on the basic form of recompression cycle (see Figure 1 below),

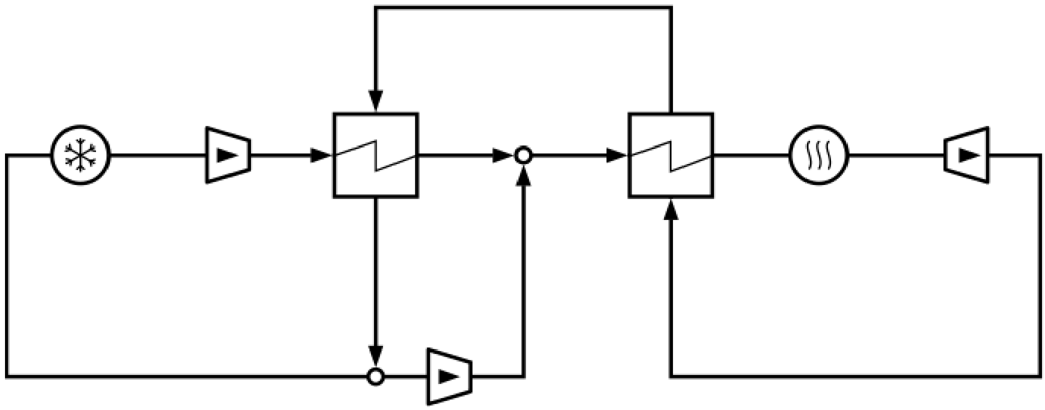

Figure 1: basic form of recompression

- Then: a pre-selection of 6 basic cycles (with possible additional modification from the base) has been identified by the partners (description in sections 1.2 and 1.3 below).

1.1 Preliminary sensibility analysis on "base form" cycle

This section describes the implementation of the sensibility analysis done on the basic form of recompression cycle. As explained, the sCO_2 Brayton cycle is very sensitive to many parameters. In this context, the pressure drops, the maximum temperature/pressure and the cooling temperature impacts on the cycle performance (cycle net efficiency) are assessed regarding the setting displayed in the Table 1:

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Table 1: setting of the sensibility analysis applied to basic recompression cycle

Modified parameter	New values	Cycle label
Heat exchanger and boiler pressure drops:	H.Ex pressure drops = 0.1% of inlet pressure Boiler pressure drops = 0.1 MPa	A
Heat exchanger and boiler pressure drops:	H.Ex pressure drops = 1% of inlet pressure Boiler pressure drops = 0.5 MPa	B
Boiler outlet maximal temperature	550°C (with compressor outlet pressure = 20 MPa)	C
Boiler outlet maximal temperature	700°C (with compressor outlet pressure = 30 MPa)	D
CO_2 minimal temperature (cooling temperature)	30°C	E
CO_2 minimal temperature (cooling temperature)	34°C	F

For each case, the parameters that are fixed (hypotheses and assumptions) are defined in Table 3.

1.2 List of “pre-selected” cycle architectures

The cycle numbering of analysed architectures contains two digits (#XX) and is specific to this study. The first digit indicates the “base form” of the analysed architecture and the second digit only corresponds to “additional cycle modifications” done on the “base form” (see Table 2). For examples, the cycle #11 is the “base form” of recompression cycle without any additional modification, while the cycle #12 is the recompression cycle with one reheat, etc.

Table 2: List of analyzed cycle architectures in this document. Numbering relies on two digits that respectively indicate the “base form” and the additional cycle modification.

Base form	Additional modification	Cycle Number
1 - Recompression cycle	-	11
	One reheat	12
	Double reheat	13
	One intercooling	14
	Intercooling + reheat	15
	HTR bypass	16
2 - Partial cooling cycle	-	21

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Base form	Additional modification	Cycle Number
	One reheat	22
	Double reheat	23
	HTR bypass	24
3 - Pre-compression cycle	-	31
	One reheat	32
	Double reheat	33
	HTR bypass	34
4 - Turbine split-flow cycle	-	41
	One reheat	42
	LTR bypass	43
5 - Preheating cycle	-	51
	One reheat	52
	Double reheat	53
6 - Split-expansion cycle	-	61

1.3 Simplified process flow diagram (PFD) of "pre-selected" architectures

The section shows simplified process flow diagram of studied architectures' "base form". The detailed process flow diagrams (with specific component names) are given in appendix.

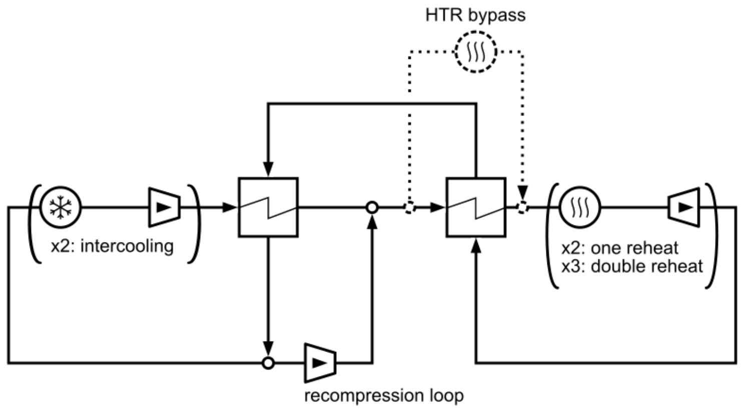

Figure 2: Recompression cycles

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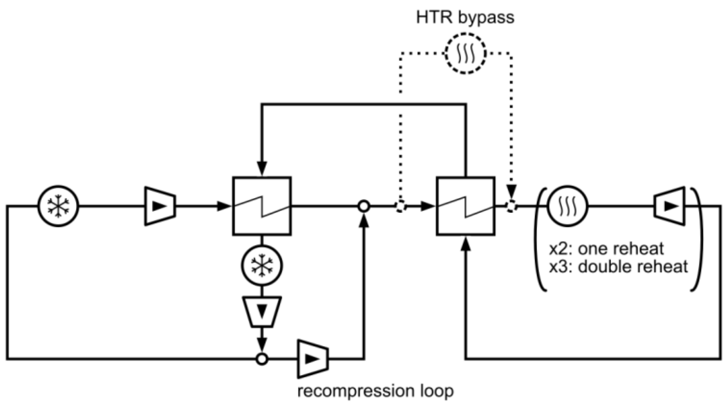

Figure 3: Partial cooling cycles

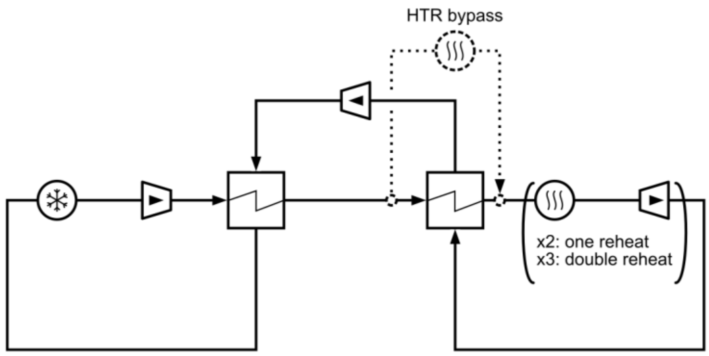

Figure 4: Pre-compression cycles

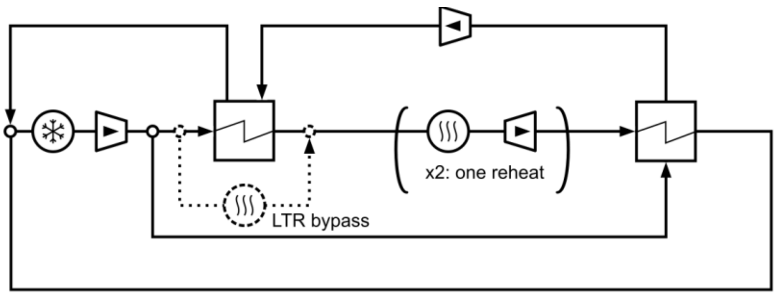

Figure 5: Turbine split flow cycles

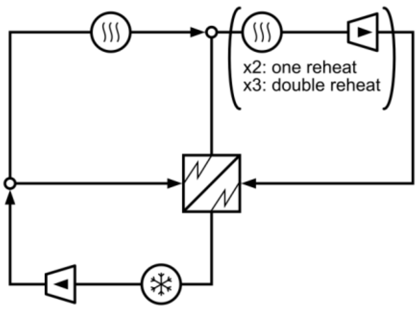

Figure 6: Preheating cycles

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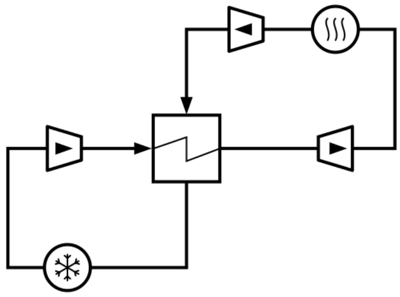

Figure 7: Split expansion cycle

All these cycle architectures are analysed by using the process modelling software AspenPlus®. The process simulation screening method to obtain the design point of each cycle architecture is based on a "sensibility analysis" survey and does not correspond to a proper optimization (cycle optimization will be done later in the WP 5). This screening method enables to assess the best cycle performances (given the fixed constraints) but also to obtain the global heat and mass balance table which is important for the components' pre-design and design steps. The process simulation of cycle architectures is done regarding several assumptions and fixed parameters as defined below (Table 3).

1.4 Hypotheses and assumptions

In this document, the RefProp (NIST) thermodynamic model is used for the process simulation. Since there is no geometry calculations (and thus, no velocity calculations), **static thermodynamic quantities** are given in this document.

Table 3: fixed parameters and assumption for the process simulations of pre-selected cycle architectures

Parameter	Unit	Value	Comment
Net cycle production	MWe	25	This value enables to calculate the required CO_2 mass flow and the boiler/cooler duty (this assumption shall not be changed until the scaling-up assessment at the end of the project)
MSCUSXXT2	°C	33	Lowest CO_2 temperature, fixed in order to enable some light temperature variation without involving CO_2 phase change (this assumption could change regarding further optimization results of the WP5 and 6. Also, this value will be changed when assessing the impact of "water cooled" sCO_2 cycle by EDF and POLIMI in WP6).
MSHSOXXT2	°C	620	Boiler outlet maximal temperature (this assumption is not expected to change during

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Parameter	Unit	Value	Comment
			the project, except if specified by UJV for material reason).
MSCOMXXP2	MPa	25.0	Main compressor maximal pressure outlet, fixed in order to avoid important stresses in the boiler. **Note**: only in cycle architecture #61, this pressure is set to 30 MPa since there is a turbine before the boiler (this assumptions is not expected to change).
Compressors isentropic efficiency	%	80	(Performance maps are necessary for part-load simulation. They will be provided by BHGE).
Turbine isentropic efficiency	%	90	(Performance maps are necessary for part-load simulation. They will be provided by BHGE).
Pressure drops in the heater (MSHSO)	MPa	No reheat: 0.25 One reheat: 0.2 + 0.1 Two reheats: 0.2+0.1+0.1 HTR/LTR bypass : 0.1+0.2	Simplified pressure drop model is applied in this document. It is assumed the pressure drop depends on the boiler structure (number of reheat). This rough hypothesis is to be refined in further studies because pressure drops also depends on the mass flow... (this hypothesis is expected to be refined during the project in WP2. As pressure drops depends on the cycle configurations and parameters such as mass flow, pressure, temperature, component size…, this refinement will be done once the cycle architecture is chosen).
Pressure drops MSRCUXX	%	0.5	This rough hypothesis is to be refined in further studies (as for the boiler pressure drops, this hypothesis should be refined once the cycle architecture is selected – WP4).
Pressure drops MSCUS	%	0.5	This rough hypothesis is to be refined in further studies (same comment).
Maximum number of intercooling	1		(This assumption is not expected to be changed during the project).
Auxiliary consumption	MWe	-	Not considered in this document as a first simplified estimation (further details on the global cycle design will come later during the WP5 and 6).
Boiler maximal efficiency	%	94	This is a first assumption that can be modified later with further data about the boiler design
CO_2 purity	%	100	Pure CO_2 is used for these calculations.

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1.5 Boiler performance assessment

As explained in previous section, a coal boiler efficiency depends on the power cycle heat-integration. The coal boiler provides both "high" and "low temperature heat that must be recovered by the power cycle. If it remains some heat at the stack outlet, the boiler efficiency decreases. Indeed, it means that less heat have been recovered from the combustion.

In this context, the CO_2 temperature at the boiler inlet is important and affects the boiler performance. This correlation is complicated as many parameters interact. However, the following equation enables to **roughly** assess the boiler performance drop with the variation of the CO_2 temperature at the boiler inlet:

$$\eta_{boiler}[\%] = \eta_{max}[\%] \times \left(1 - 0.5 \times \left(1 - \frac{1200 - \max\ (350\,; T_{in}\,[°C] + 10)}{1200 - 350}\right)\right)$$

Where:

η_{max} is the maximal boiler efficiency in % (assumed to be 94% in this document);

T_{in} is the minimal CO_2 temperature at the boiler inlet in °C.

In these conditions, the boiler efficiency drops from 94% to about 85% if the CO_2 enters the boiler at about 500 °C.

Results

The overall heat and mass balance tables are available in appendix. This section only focuses on main parameters such as the net cycle efficiency (defined as [turbines work minus compressors work] over boiler duty), the duty to reject at the cooler (MSCUSXXD), the minimal CO_2 temperature at the boiler inlet (MSHSOXXT1), and the total CO_2 mass flow. Indeed, a compromise must be found between selecting only one cycle to be fully designed (this solution is considered to be too restrictive and risky since it's possible that the results of the future detailed cycle optimization (WP5) can lead to different conclusions) and more than 3 cycles to be fully designed (time-consuming process). In this context, the parameters cited above enable to quickly compare the pre-selected cycle architectures and reduce the number of interesting architecture to be fully designed (2 or 3 at maximum) without being too restrictive.

First, some general conclusions concerning all studied architectures about the effects of "additional modifications" on the "base form" are given in sections 2.1 to 2.3. The results of the sensibility analysis of the recompression "base form" is given in section 2.4. Finally, tables with detailed results is given in order to compare each studied architecture in section 2.5.

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2.1 General effect of reheating

The reheating process consists in dividing the expansion step of the process and to send back the sCO_2 in the boiler to heat it again before finishing the expansion step. The number or reheat usually stands between 0 and 2. As a direct consequence of reheating process (single or double), the CO_2 temperature at the end of the expansion step is higher (for a reheated cycle) than for the "basic form" (i.e. the HTR maximal temperature (MSRCU01T1) is higher for reheating cycles), which means more heat duty is transferable in the HRT (MSRCU01D), reducing the heat to be provided by the boiler and thus, increases the cycle efficiency (in other words, reheating cycles have a better heat recovery ratio than "base form" cycles). On the other hand, this means that the temperature at the boiler inlet also increases compared to "base form" cycle, which negatively impacts the boiler as explained above (coal-boiler performances depend on the amount of heat recovered from the boiler: if CO_2 enters the boiler at high temperature, a large amount of the boiler heat is not recovered).

Double reheat process logically further emphasizes this phenomenon: the cycle efficiency, but also the CO_2 temperature at the boiler inlet, both increase.

As a general statement, the CO_2 mass flow is reduced when the cycle efficiency increases at fixed electricity power production. In the study constraints, the electricity power production is fixed to be 25 MW_e: thus, the CO_2 mass flow decreases with the application of reheating process.

2.2 General effect of intercooling

The intercooling consists in dividing the compression stage in two (or several) parts between which the CO_2 is cooled before finishing the compression stage. This intercooling process thus enables to reduce the temperature during (and at the end) of the compression step. Thus, the compression work is reduced (compression work of a gas increase with its temperature). This process modification also enables a higher expansion ratio than for the "base form" cycle, globally reducing the temperature in the whole cycle (higher expansion ratio at fixed maximal pressure means lower turbine outlet pressure that implies lower temperature at the HTR hot side inlet and thus, lower maximal possible temperature at the boiler inlet compared to "base form" cycle).

To sum up, intercooling enables to slightly increase the cycle efficiency (and thus the CO_2 mass flow rate at fixed electricity production) while ensuring at slightly lower CO_2 temperature at the boiler inlet.

2.3 General effect of LTR/HTR bypass

The high (or low) temperature recuperator bypass consists in extracting a fraction of the main CO_2 mass flow at the H(or L)TR inlet. This process modification enables to have different CO_2 mass flow between the hot and the cold side of the recuperators. High variation of the CO_2

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physical properties with pressure and temperature are responsible for high losses in the recuperators [Utamura, 2010]. This is why recompression cycles are recommended for sCO_2 Brayton cycle: indeed, this method enable to have different CO_2 mass flows at the cold and hot side of recuperators (LTR). In these conditions, it is possible to reduce the gap of the CO_2 temperature between the cold and the hot side of recuperators. This method work for the LTR (where the CO_2 physical properties suffer from important variations), but it the HTR, the CO_2 mass flow is equal in both cold and hot sides of the recuperator [Bai et al, 2018].

The HTR bypass thus enables to differentiate the CO_2 mass flow rate to reduce the gap of the CO_2 temperature between the cold and the hot side. Also, this method enable to preheat the "bypassing CO_2 flow" in the boiler at a lower temperature than without bypass.

To sum up, this process modification has a minor impact on the cycle performance and enables to reduce the minimal CO_2 temperature at the boiler inlet (note that only a fraction of the total CO_2 mass flow is concerned which mitigates the "boiler inlet temperature reduction" effect. This fraction depends on the cycle configuration and fixed parameters).

2.4 Sensibility analysis results (base form)

The sensibility analysis main results are summarized on the following Table 4 (the detailed heat and mass balance tables are given in appendix). Note that the cycle number 11 is the "base form" of the recompression cycle with reference parameters and assumptions while cycles "A to F" are related to the sensibility analysis (see Table 1 above):

Table 4: Sensibility analysis on the recompression "base form" cycle (from A to F)

Sensibility analysis on the recompression "base form" cycle (from A to C)							
Cycle number →	**11**	**A**	**B**	**C**	**D**	**E**	**F**
Cycle net efficiency (%)	46.08	46.68 (+0.6)	45.16 (-0.92)	41.98 (-4.1)	49.70 (+3.62)	46.72 (+0.64)	45.78 (-0.3)
Heat rejected at the cooler (MWth)	28.54	27.80 (-0.74)	29.58 (+1.04)	33.75 (+5.21)	24.59 (-3.95)	27.80 (-0.74)	28.85 (+0.31)
Minimal boiler inlet temperature (°C)	439.3	436.3 (-3)	443.1 (+3.8)	402.4 (-36.9)	487.9 (+48.6)	432.6 (-6.7)	442.0 (+2.7)
Boiler estimated efficiency (%)	88,5	88,7 (+0.2)	88,3 (-0.2)	90,5 (+2)	85,8 (-2.7)	88,9 (+0.4)	88,4 (-0.1)
Total CO_2 mass flow (kg/s)	239.5	232.5 (-7)	249.4 (+9.9)	327.5 (+88)	186.5 (-53)	228.0 (-11.5)	244.9 (+5.4)

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As expected, the cycle pressure drops and the boiler outlet temperature have high impact on the cycle efficiency. Cooling temperature and main compressor outlet pressure have lower impact of the cycle performance.

As the electrical power production is fixed, better efficiency implies a lower CO_2 mass flow. Indeed, the efficiency improvement is mainly due to the amount of "recovered heat" in the recuperators, especially in the HTR. The cycle temperature balance is also impact by the pressure drops. Also, the "minimal boiler inlet temperature" is indeed impacted by the boiler outlet temperature: for a given cycle, higher boiler outlet temperature leads to higher turbine outlet temperature, thus, a higher "heat recovery" in the HTR and finally, a higher boiler inlet temperature.

Cooling temperature variation study shows that the cycle performance will be affected by variability on the cooling temperature (flexibility).

Figure 8 illustrates the net cycle efficiency (in %) sensibility with variation of the main compressor outlet pressure (MSCOM01P2 in MPa) for 3 different boiler outlet temperatures (MSHSOT2 in °C). It can be observed that, as predicted in [Dostal, 2004], the maximum cycle temperature has a stronger impact on the cycle next efficiency that the main compressor outlet pressure, which means that efforts to improve the net cycle efficiency must be concentrated to solve "high CO_2 temperature related issues" more than "high pressure related issues". Of course, this conclusion is drawn regarding only the net cycle efficiency and should be balanced by considering other aspects (economic, flexibility…).

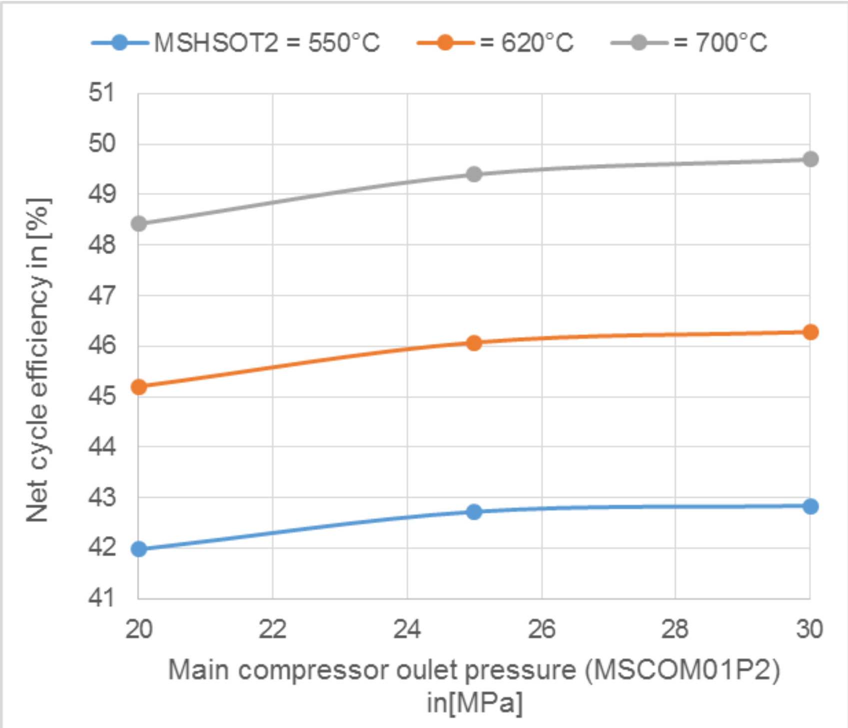

Figure 8: Recompression "base form" net cycle efficiency (in %) as a function of the main compressor outlet pressure (MSCOM01P2 in MPa) for 3 different boiler outlet temperatures (MSHSOT2 in °C)

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2.5 Cycle performance: Results comparison

This section enables to compare the studied architecture regarding the main parameters cited in the Table 3 above. Note that numbering is related to cycle architectures as explained in section 1.2.

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Table 5: Summary of main results of the recompression cycles (cycle numbers: 11 to 16)

Recompression cycles (from 11 to 16)						
Cycle number→	**11**	**12**	**13**	**14**	**15**	**16**
Cycle net efficiency (%)	46.08	48.38 (+2.30)	48.97 (+2.90)	46.52 (+0.45)	48.06 (+1.99)	46.13 (~ =)
Heat rejected at the cooler (MWth)	28.54	26.37 (-2.17)	26.02 (-2.52)	28.03 (-0.51)	26.35 (-2.19)	28.46 (~ =)
Minimal boiler inlet temperature (°C) AND Fraction of the CO_2 mass flow (%)	439.3	514.6 (+ 75.3) 100%	541.2 (+101.9) 100%	431.3 (-8.0) 100%	489.4 (+50.1) 100%	194.4 (-244.9) 11%
Boiler estimated efficiency (%)	88,5	84,3 (-4.2)	82,9 (-5.6)	89,0 (+0.4)	85,7 (-2.8)	94,0 (+5.5)
Total CO_2 mass flow (kg/s)	239.5	221.6 (-17.9)	217.6 (-21.9)	227.5 (-12.0)	213.4 (-26.1)	239.0 (-0.5)

As explained above in general architecture modification effects, reheating (#12&13) improve the cycle efficiency (and thus, reducing the CO_2 mass flow for a fixed electrical power output) while increasing the minimal boiler inlet temperature (leading to a reduction of the boiler efficiency, and thus, a possible reduction of the global power plant efficiency which is the product of the boiler efficiency time the cycle efficiency) and the number of turbomachinery (can be expensive to have several turbomachinery working at very high temperature). The reheating process modification is then interesting for performances but can be a detrimental from a global power plant performance or cost point of view.

The intercooling (#14) cycle enables to both slightly increase the cycle efficiency while reducing the minimal CO_2 boiler inlet temperature (compared to "base form" #11) which is more interesting from a global cycle performance point of view. However, this architecture means addition of one compressor (additional costs) which operates close to the CO_2 critical point (complex control and instrumentation management).

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The combination of intercooling and reheating processes (#15) is further improving the efficiency compared to sole intercooling process (#14) but it cancels the benefits of lowering the minimal boiler inlet temperature. Furthermore, the number of turbomachinery is high (increasing the expected cost).

The HTR bypass process (#16) enables to reduce the boiler inlet temperature but only for a fraction of the total CO_2 mass flow (~11%) without modifying significantly the performance and the layout of the "base form" (#11).

In next tables, the results of the "base form" of recompression cycle (#11) are shown as reference for comparison with other architectures.

Table 6: Summary of main results for Partial cooling cycles (cycle numbers: 21 to 24)

Partial cooling cycles (from 21 to 24)					
Cycle number →	**11**	**21**	**22**	**23**	**24**
Cycle net efficiency (%)	46.08	40.22 (-5.85)	41.97 (-4.10)	42.77 (-3.30)	40.26 (-5.81)
Heat rejected at the cooler (MWth)	28.54	36.56 (+8.02)	34.22 (+5.68)	33.50 (+4.96)	36.47 (+7.93)
Minimal boiler inlet temperature (°C) **AND** **Fraction of the CO_2 mass flow (%)**	439.3	371.6 (-67.7) 100%	429.6 (-9.70) 100%	467.7 (+28.4) 100%	69.8 (-369.5) 21%
Boiler estimated efficiency (%)	88,5	92,3 (+3.7)	89,0 (+0.5)	86,9 (-1.6)	94,0 (+5.5)
Total CO_2 mass flow (kg/s)	239.5	200.1 (-39.4)	187.3 (-52.2)	183.3 (-56.2)	199.5 (-40.0)

As for the "recompression cycles", the global trend for "partial cooling cycles" (#21to24) are similar. Reheating processes (#22&23) enable to enhance the cycle performance compared to the "base form" (#21) and the HTR bypass (#24) enables to drastically reduce the minimal boiler inlet temperature for a fraction of the total CO_2 mass flow (21%). Indeed, in partial cooling cycles, the LTR is almost useless (small amount of heat transferred through the LTR) while the HTR is recovering a large amount of heat. In these conditions, the CO_2 temperature at the HTR cold side inlet in significantly lower than in recompression cycles. Note that simple recuperated Brayton cycle (without LTR and without secondary compressor #00) has a cycle

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net efficiency of 39.8% is the same operating conditions (which is less than 1%pt worse than #21) proving that "partial cooling" cycles are expected to have rather low performances in the given constraints.

Compared to the "base form" of the recompression (#11), the partial cooling cycles (#21to24) do not provide performance improvement. However, the minimal boiler inlet temperature is significantly lower (except for #23) and the CO_2 mass flow is also lower, which can be seen as an opportunity to have a better boiler "heat integration" (and thus a higher boiler efficiency) and to reduce challenges related to high CO_2 mass flow.

Table 7: Summary of main results for Pre compression cycles (cycle numbers: 31 to 34)

Pre compression cycles (from 31 to 34)					
Cycle number →	**11**	**31**	**32**	**33**	**34**
Cycle net efficiency (%)	46.08	42.99 (-3.09)	45.22 (-0.86)	45.72 (-0.36)	42.99 (-3.08)
Heat rejected at the cooler (MWth)	28.54	32.38 (+3.84)	29.94 (+1.4)	29.54 (+1)	32.39 (+3.85)
Minimal boiler inlet temperature (°C) **AND** **Fraction of the CO_2 mass flow (%)**	439.3	453.9 (+14.6) 100%	528.0 (+88.7) 100%	555.4 (+116.1) 100%	192.2 (-247.1) 10%
Boiler estimated efficiency (%)	88,5	87,7 (-0.8)	83,6 (-4.9)	82,1 (-6.4)	94,0 (+5.5)
Total CO_2 mass flow (kg/s)	239.5	279.4 (+39.9)	264.4 (+29.9)	260.6 (+21.1)	278.3 (+38.8)

The pre-compression cycles (#31to34) offers better performances than partial cooling cycles (#21to24) but lower than recompression cycle (#11to16). General conclusions about architecture modification effects as explained above can also be observed in pre-compression cycles. However, the minimal boiler inlet temperature tends to increase compared to recompression cycle "base form" (#11), except for the HTR bypass (#34). Furthermore, these pre-compression cycles undergo high compression work since the inlet temperature of the main compression (MSCOM01T1) is higher than in other cycles (due to the position of the

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compressor at the HTR hot side outlet). Thus, the CO_2 mass flow in these cycles significantly increase compared to the cycle #11.

Table 8: summary of Turbine split flow cycles (cycle numbers: 41 to 43)

Turbine split flow cycles (from 41 to 43)				
Cycle number →	**11**	**41**	**42**	**43**
Cycle net efficiency (%)	46.08	37.82 (-8.26)	40.81 (-5.26)	37.81 (-8.26)
Heat rejected at the cooler (MWth)	28.54	40.71 (+12.17)	36.22 (+7.68)	40.67 (+12.13)
Minimal boiler inlet temperature (°C) **AND** **Fraction of the CO_2 mass flow (%)**	439.3	200.6 (-238.7) 100%	288.5 (-150.8) 100%	75.0 (-364.3) 43%
Total CO_2 mass flow (kg/s)	239.5	220.7 (-18.8)	196.3 (-43.2)	220.7 (-18.8)

The turbine split-flow cycles (#41to43) are only interesting for the low minimal boiler inlet temperature. Indeed, in these architectures, the CO_2 that going through the boiler is only passing through the LTR (the HTR being situated after the main expansion process). Then, the CO_2 upper temperature limit at the boiler inlet is around 289°C for these "turbine split-flow" cycles. The main drawback of these cycle architectures is their low performance (similar to simple recuperated Brayton cycle performance #00).

Table 9: Summary of main results for Preheating cycles (cycle numbers: 51 to 53)

Preheating cycles (from 51 to 53)				
Cycle number →	**11**	**51**	**52**	**53**
Cycle net efficiency (%)	46.08	40.16 (-5.91)	42.10 (-3.97)	42.60 (-3.47)
Heat rejected at the cooler (MWth)	28.54	36.59 (+8.05)	34.10 (+5.56)	33.52 (+4.98)

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Minimal boiler inlet temperature (°C) **AND** **Fraction of the CO_2 mass flow (%)**	439.3	86.0 (-353.3) 20.5%	86.0 (-353.3) 18.1%	86.0 (-353.3) 17.3%
Total CO_2 mass flow (kg/s)	239.5	203.5 (-36.0)	189.6 (-49.9)	186.4 (-53.1)

The preheating cycles (#51to53) are also only interesting for their low minimal boiler inlet temperature. Indeed, a fraction of the CO_2 mass flow at the compressor outlet directly goes to the boiler (without passing through the recuperator). The other fraction is going through the recuperators first before going to the boiler. The Simplicity of this layout can also be outlined, with slightly better performances than turbine split-flow cycles (#41to43). The performances are comparable to partial cooling cycles (#21to24) but with simpler layout (only one compressor against 3 and one cooler against 2).

Table 10: Summary of the main results for the Split expansion cycle (61)

Split expansion cycle (61)		
Cycle number →	**11**	**61**
Cycle net efficiency (%)	46.08	39.73 (-6.35)
Heat rejected at the cooler (MWth)	28.54	37.33 (+8.75)
Minimal boiler inlet temperature (°C)	439.3	351.8 (-87.5)
Total CO_2 mass flow (kg/s)	239.5	190.4 (-49.1)

The maximum pressure value constraint of 25 MPa for other cycles than the "split expansion" cycle (#61) has been chosen to avoid important mechanical stresses in the boiler. Since there is a turbine before the boiler in the split-expansion cycle (#61), there is no reason to keep the 25 MPa maximal pressure limit at the compressor outlet. Thus, the main compressor outlet pressure has been set to 30 MPa only for this case. Even with this exception (which is

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favourable to the cycle efficiency), the cycle performance of the split-expansion cycle are very low (comparable to simple recuperated Brayton cycle with the 25 MPa unfavourable maximal pressure constraints #00) which means there is no benefits of using this cycle layout at all.

Limitation of the study and conclusions

The aim of this study is to do a first rough estimation of cycle behavior depending on their architectures in order to compare their main parameters while fixing some constraints. This first estimation is done in order to pre-select interesting cycle architectures that worth being optimized in a second step (results of the deliverable D1.3). To do so, many simplified hypothesis are assumed in the simulation models. Some of these assumptions must be reconsidered in further simulation, especially the pressure drops that have been roughly estimated for this deliverable (the sensibility analysis done on the "base form" of the recompression cycle (#11) shows that a sCO_2 Brayton cycle is very sensitive to assumptions and parameter values). Indeed, in this study, the pressure drops have been set as fixed values (simplified model) while these values should depends on many parameters such as CO_2 pressure, temperature, component geometry and heat duty (for example, in some cycle architectures, the distribution of recovered heat in the HTR and LTR is not equal. Most of time, the HTR duty is much higher than for the LRT). For the boiler, the pressure drops distribution is also complicated and requires (at least) a rough geometry to be more accurate.

Also, this study is only focusing on the net cycle performances without considering the boiler efficiency nor the auxiliary consumptions. These data will further be included in next detailed studies on WP2 to 6.

However, despite these limitations, the obtained results enable to observe global trends to compare the existing cycle configurations and to eliminate the inappropriate architectures that suffer from more drawbacks than advantages (in the given constrained framework). Indeed, the obtained results enable to see how to improve the cycle performances without increasing the minimal boiler inlet temperature, while insuring a rather simple cycle layout.

Coupled with the deliverable D1.2, this report will enable to select a restricted number of interesting architectures (2 or 3) to study in next steps of the sCO_2-Flex project (see D1.3). However, as a first conclusions, cycle architectures such as "Preheating", "Turbine split flow" and "Split expansion" can be excluded from the pre-selection list (which means the final selection will be done with "recompression", "partial cooling" and "pre-compression" configurations).

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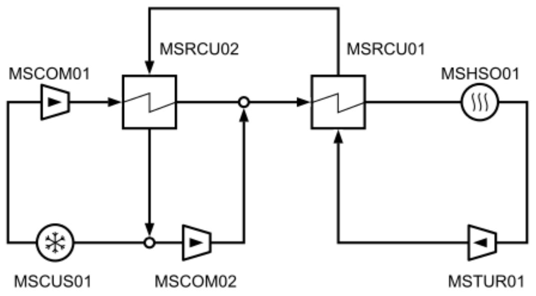
Appendix

A. Process flow diagrams

11



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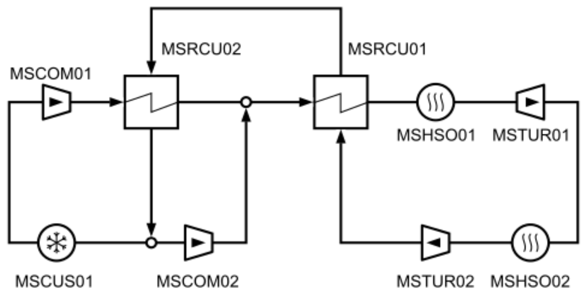

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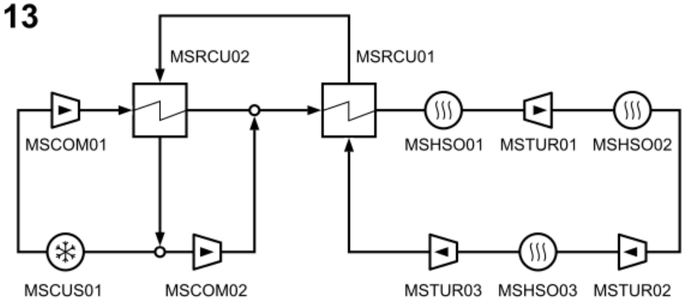

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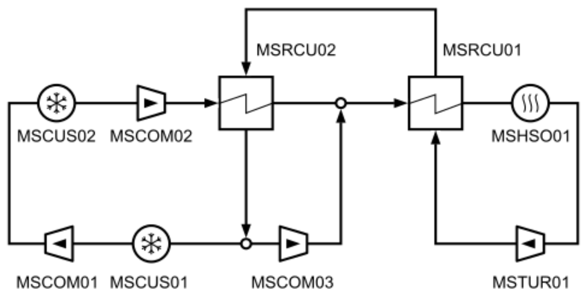

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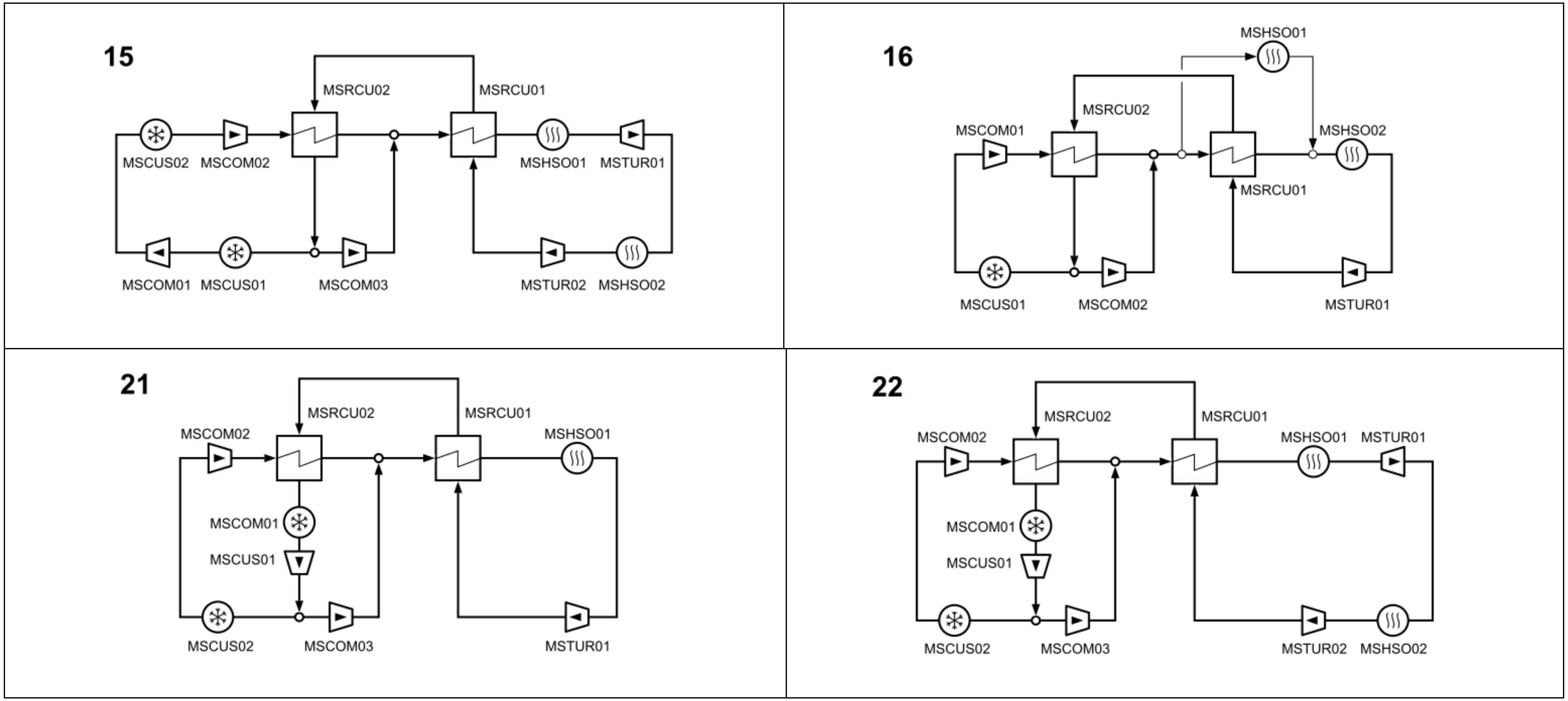

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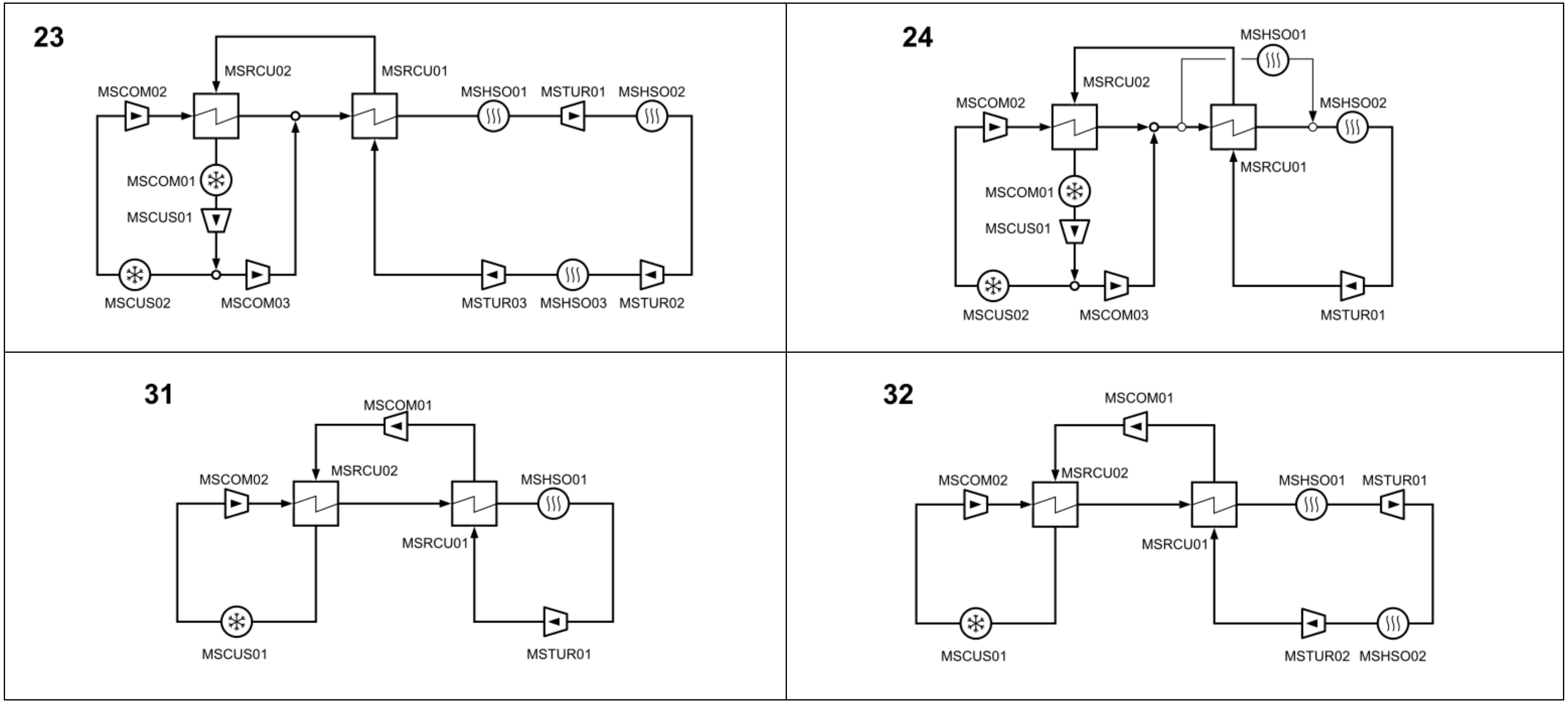

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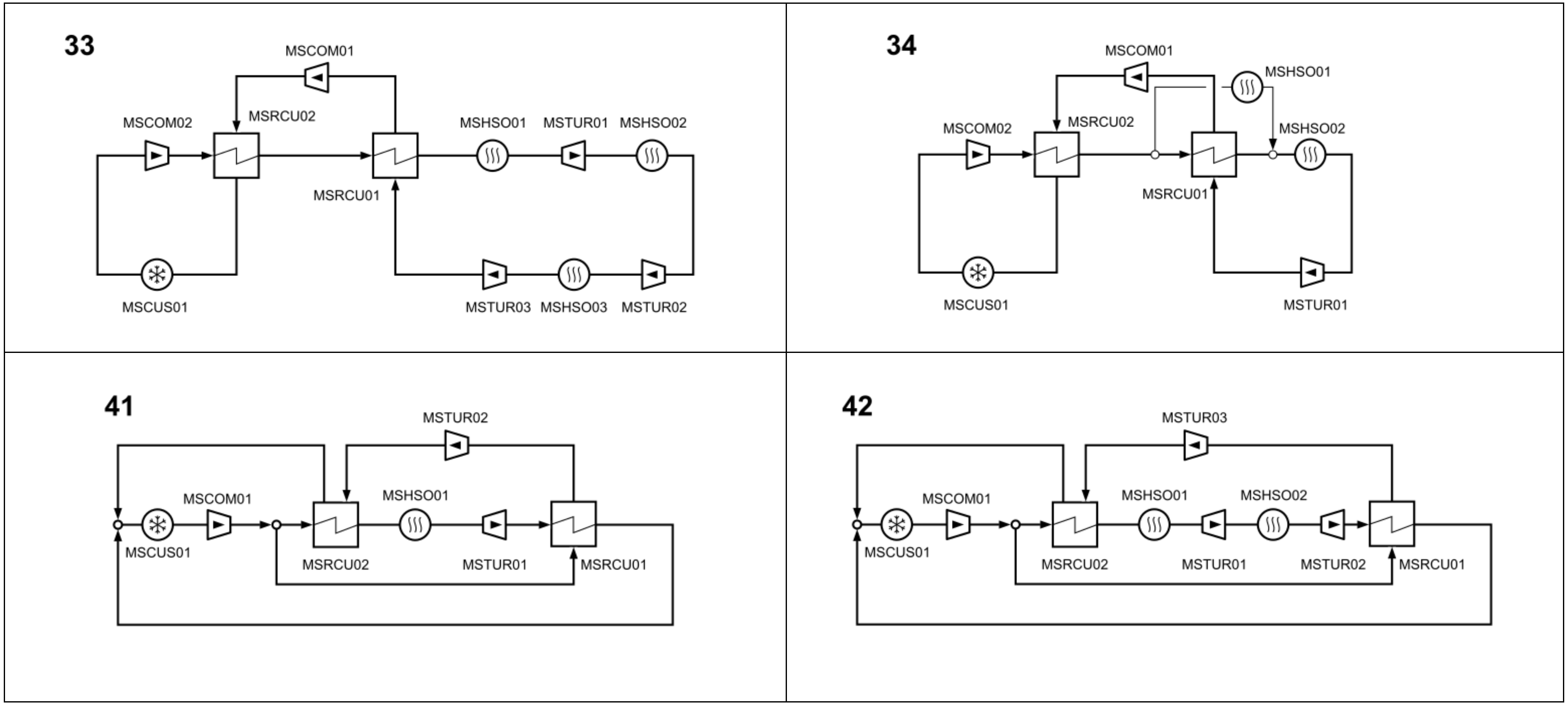

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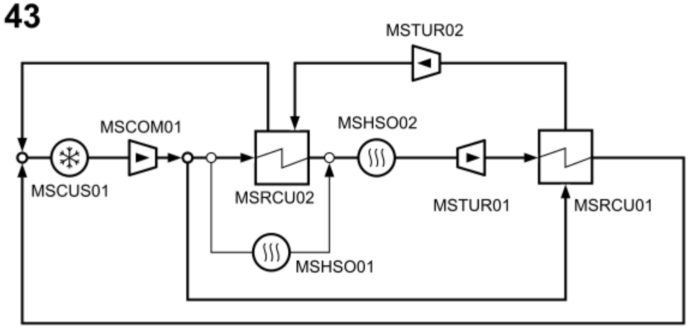
43



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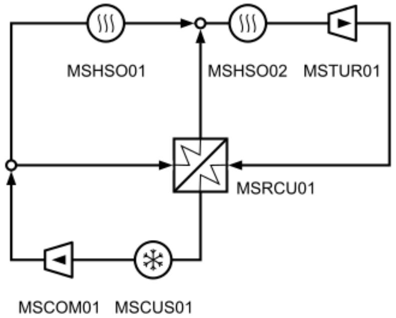

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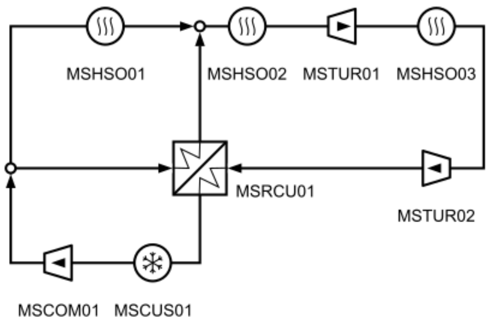

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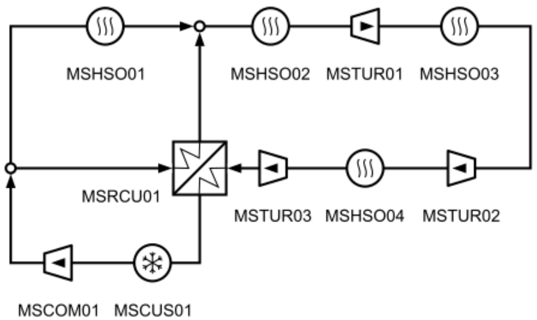

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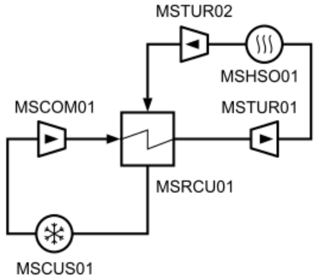
61



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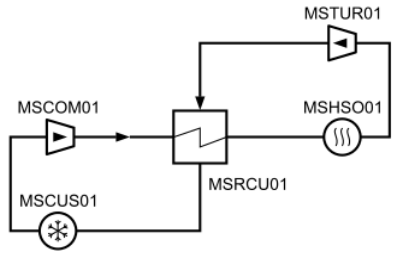

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B. Heat and mass balance

B.1. Sensibility analysis of the "base form" of recompression cycle (A to F)

Component	Parameter	Unit	11 (ref)	A	B	C	D	E	F
MSCUS01 (cooler)	T1	°C	79.9	81.2	80.4	75.4	85.4	70.5	81.5
	P1	MPa	8.02	7.926	8.037	7.871	8.118	7.772	8.217
	T2	°C	33.0	33.0	33.0	33.0	33.0	30.0	34.0
	P2	MPa	7.979	7.926	7.956	7.831	8.078	7.733	8.176
	D	MWth	28.54	27.80	29.58	33.75	24.59	27.80	28.85
	M1	kg/s	154.1	149.8	160.1	197.3	125.7	144.8	158.5
MSCOM01 (compressor)	T1	°C	33.0	33.0	33.0	33.0	33.0	30.0	34.0
	P1	MPa	7.979	7.926	7.956	7.831	8.078	7.733	8.176
	T2	°C	69.9	71.2	70.4	65.5	75.3	60.5	71.5
	P2	MPa	25	25	25	20	30	25	25
	E	MWe	4.73	4.66	4.94	4.64	4.79	4.17	4.87
	M1	kg/s	154.1	149.8	160.1	197.3	125.7	144.8	158.5
MSCOM02 (compressor)	T1	°C	79.9	81.2	80.4	75.4	85.4	70.5	81.5
	P1	MPa	8.019	7.934	8.037	7.871	8.118	7.772	8.217
	T2	°C	194.8	198.0	194.2	166.8	220.3	185.0	193.4
	P2	MPa	24.875	24.975	24.750	19.9	29.850	24.875	24.875
	E	MWe	7.13	7.08	7.42	8.36	6.23	6.78	7.05
	M1	kg/s	85.4	82.6	89.3	130.2	60.8	83.2	86.4
MSRCU01	T1	°C	481.9	478.1	485.8	442.6	532.3	478.3	484.7

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Component	Parameter	Unit	11 (ref)	A	B	C	D	E	F
(HTR)	P1	MPa	8.10	7.950	8.20	7.950	8.20	7.850	8.30
	T2	°C	204.5	207.9	204.3	176.8	230.3	195.1	203.3
	P2	MPa	8.06	7.942	8.118	7.910	8.159	7.811	8.259
	T3	°C	194.5	197.9	194.3	166.8	220.3	185.1	193.3
	P3	MPa	24.875	24.975	24.750	19.9	29.850	24.875	24.875
	T4	°C	439.3	436.3	443.1	402.4	487.9	432.6	442.0
	P4	MPa	24.750	24.950	24.500	19.8	29.70	24.750	24.750
	D	MWth	76.3	72.06	80.71	99.43	65.23	74.00	79.29
	M1	kg/s	239.5	232.5	249.4	327,5	186.5	228.0	244.9
	M3	kg/s	239.5	232.5	249.4	327.5	186.5	228.0	244.9
MSRCU02 (LTR)	T1	°C	204.5	207.9	204.3	176.3	230.3	195.1	203.3
	P1	MPa	8.06	7.942	8.118	7.910	8.159	7.811	8.259
	T2	°C	79.9	81.2	80.4	75.4	85.4	70.5	81.5
	P2	MPa	8.019	7.934	8.037	7.871	8.118	7.772	8.217
	T3	°C	69.9	71.2	70.4	65.5	75.3	60.5	71.5
	P3	MPa	25	25	25	20	30	25	25
	T4	°C	194.2	197.9	194.3	166.8	220.3	185.1	193.3
	P4	MPa	24.875	24.975	24.750	19.9	29.850	24.875	24.875
	D	MWth	36.7	35.98	37.95	41.77	32.65	35.43	36.89
	M1	kg/s	239.5	232.5	249.4	327.5	186.5	228.0	244.9
	M3	kg/s	154.1	149.8	160.1	197,3	125.7	144.8	158.5
MSHSO01 (heater)	T1	°C	439.3	436.3	443.1	402.4	487.9	432.6	442.0
	P1	MPa	24.750	24.950	24.500	19.8	29.70	24.875	24.750
	T2	°C	620.0	620.0	620.0	550.0	700.0	620	620.0

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Component	Parameter	Unit	11 (ref)	A	B	C	D	E	F
	P2	MPa	24.5	24.850	24.0	19.55	29.450	24.500	24.500
	D	MWth	54.23	53.51	55.30	59.49	50.31	53.55	54.62
	M1	kg/s	239.5	232.5	249.4	327.5	186.5	228.0	244.9
MSTUR01 (turbine)	T1	°C	620.0	620.0	620.0	550.0	700.0	620.0	620.0
	P1	MPa	24.5	24.850	24.0	19.55	29.450	24.500	24.500
	T2	°C	481.9	478.1	485.8	442.6	532.3	478.3	484.7
	P2	MPa	8.1	7.950	8.20	7.950	8.20	7.850	8.30
	E	MWe	36.84	36.72	37.33	37.98	36.02	35.96	36.93
	M1	kg/s	239.5	232.5	249.4	327.5	186.5	228.0	244.9
Total cooling duty MSCUSXX	D	MWth	28.54	27.80	29.58	33.75	24.59	27.80	28.85
Total heating duty MSHSOXX	D	MWth	54.23	53.51	55.30	59.49	50.31	53.55	54.62
Total compression work MSCOMXX	E	MWe	-11.85	-11.74	-12.36	-13.01	-11.01	-10.95	11.92
Total expansion work MSTURXX	E	MWe	36.84	36.72	37.33	37.98	36.02	35.96	36.93
Net cycle efficiency	**EFF**	**%**	**46.075**	**46.677**	**45.163**	**41.977**	**49.696**	**46.717**	**45.784**
Lowest boiler inlet temp.	T	°C	439.3	436.3	443.1	402.4	487.9	432.6	442.0

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B.2. Recompression cycles (from 11 to 16)

Component	Parameter	Unit	11	12	13	14	15	16
MSCUS01 (cooler)	T1	°C	79.9	79.9	79.9	65.9	66.2	80.0
	P1	MPa	8.02	8.016	8.016	7.871	7.871	8.019
	T2	°C	33.0	33.0	33.0	33.0	33.0	33.0
	P2	MPa	7.979	7.979	7.979	7.831	7.831	7.979
	D	MWth	28.54	26.37	26.0	22.62	21.28	28.54
	M1	kg/s	154.1	142.5	140.0	145.3	136.2	153.7
MSCUS02 (cooler)	T1	°C	-	-	-	41.1	41.1	-
	P1	MPa	-	-	-	10.0	10.0	-
	T2	°C	-	-	-	33.0	33.0	-
	P2	MPa	-	-	-	9.950	9.950	-
	D	MWth	-	-	-	5.41	5.07	-
	M1	kg/s	-	-	-	145.3	136.2	-
MSCOM01 (compressor)	T1	°C	33.0	33.0	33.0	33.0	33.0	33.0
	P1	MPa	7.979	7.979	7.979	7.831	7.831	7.979
	T2	°C	69.9	69.9	69.9	41.1	41.1	69.9
	P2	MPa	25	25	25	25	25	25
	E	MWe	4.73	4.37	4.29	0.67	0.63	4.71
	M1	kg/s	154.1	142.5	140.0	145.3	136.2	153.7
MSCOM02 (compressor)	T1	°C	79.9	79.9	79.9	33.0	33.0	80.0
	P1	MPa	8.019	8.016	8.016	9.950	9.950	8.019
	T2	°C	194.8	194.3	195	55.9	55.9	194.6
	P2	MPa	24.875	24.875	24.875	25	25	24.875
	E	MWe	7.13	6.60	6.49	3.50	3.28	7.12
	M1	kg/s	85.4	79.1	77.5	145.3	136.2	153.7
MSCOM03	T1	°C	-	-	-	65.9	66.2	-

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Component	Parameter	Unit	11	12	13	14	15	16
(compressor)	P1	MPa	-	-	-	7.871	7.871	-
	T2	°C	-	-	-	176.6	177.0	-
	P2	MPa	-	-	-	24.875	24.875	-
	E	MWe	-	-	-	6.34	5.97	-
	M1	kg/s	-	-	-	82.2	77.2	-
MSRCU01 (HTR)	T1	°C	481.9	560.5	587.8	479.7	540.3	481.6
	P1	MPa	8.10	8.10	8.10	7.950	7.950	8.10
	T2	°C	204.5	204.2	204.9	186.5	187.0	204.4
	P2	MPa	8.06	8.06	8.060	7.910	7.910	8.06
	T3	°C	194.5	194.2	194.9	176.5	177.0	194.4
	P3	MPa	24.875	24.875	24.875	24.875	24.875	24.875
	T4	°C	439.3	514.6	541.2	431.3	489.4	470.6
	P4	MPa	24.750	24.750	24.750	24.750	24.750	24.750
	D	MWth	76.3	91.5	96.9	76.5	87.05	76.10
	M1	kg/s	239.5	221.6	217.6	227.5	213.4	239.0
	M3	kg/s	239.5	221.6	217.6	227.5	213.4	212.7
MSRCU02 (LTR)	T1	°C	204.5	204.2	204.9	186.5	187.0	204.4
	P1	MPa	8.06	8.06	8.06	7.910	7.910	8.06
	T2	°C	79.9	79.9	79.9	65.9	66.0	80.0
	P2	MPa	8.019	8.016	8.016	7.871	7.871	8.019
	T3	°C	69.9	69.9	69.9	55.9	55.9	69.9
	P3	MPa	25	25	25	25	25	25
	T4	°C	194.2	194.2	194.9	176.5	177.0	194.3
	P4	MPa	24.875	24.875	24.875	24.875	24.875	24.875
	D	MWth	36.7	33.9	33.4	35.1	33.0	36.56
	M1	kg/s	239.5	221.6	217.6	227.5	213.4	239.0
	M3	kg/s	154.1	142.5	140.0	145.3	136.2	153.7

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Component	Parameter	Unit	11	12	13	14	15	16
MSHSO01 (heater)	T1	°C	439.3	514.6	541.2	431.3	489.4	194.3
	P1	MPa	24.750	24.750	24.750	24.750	24.750	24.875
	T2	°C	620.0	620.0	620.0	620.0	620.0	471.0
	P2	MPa	24.5	24.55	24.55	24.5	24.55	24.775
	D	MWth	54.23	29.4	24.6	53.8	35.0	9.42
	M1	kg/s	239.5	221.6	217.6	227.5	213.4	26.3
MSHSO02 (heater)	T1	°C	-	537.8	563.8	-	555.6	470.6
	P1	MPa	-	13.0	16.0	-	15.0	24.750
	T2	°C	-	620.0	620.0	-	620.0	620.0
	P2	MPa	-	12.9	15.9	-	14.9	24.550
	D	MWth	-	22.3	15.2	-	17.0	44.8
	M1	kg/s	-	221.6	217.6	-	213.4	239.0
MSHSO03 (heater)	T1	°C	-	-	566.4	-	-	-
	P1	MPa	-	-	10.5	-	-	-
	T2	°C	-	-	620.0	-	-	-
	P2	MPa	-	-	10.4	-	-	-
	D	MWth	-	-	14.3	-	-	-
	M1	kg/s	-	-	217.6	-	-	-
MSTUR01 (turbine)	T1	°C	620.0	620.0	620.0	620.0	620.0	620.0
	P1	MPa	24.5	24.55	24.55	24.5	24.55	24.55
	T2	°C	481.9	537.8	563.8	479.7	555.6	481.6
	P2	MPa	8.1	13.0	16.0	7.95	15.0	8.1
	E	MWe	36.84	20.95	14.17	35.53	15.56	36.82
	M1	kg/s	239.5	221.6	217.6	227.5	213.4	239.0
MSTUR02 (turbine)	T1	°C	-	620.0	620.0	-	620.0	-
	P1	MPa	-	12.9	15.9	-	14.9	-
	T2	°C	-	560.5	566.4	-	540.3	-

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Component	Parameter	Unit	11	12	13	14	15	16
	P2	MPa	-	8.10	10.5	-	7.95	-
	E	MWe	-	15.03	13.55	-	19.30	-
	M1	kg/s	-	221.6	217.6	-	213.4	-
MSTUR03 (turbine)	T1	°C	-	-	620.0	-	-	-
	P1	MPa	-	-	10.4	-	-	-
	T2	°C	-	-	587.8	-	-	-
	P2	MPa	-	-	8.10	-	-	-
	E	MWe	-	-	8.05	-	-	-
	M1	kg/s	-	-	217.6	-	-	-
Total cooling duty MSCUSXX	D	MWth	28.54	26.37	26.02	28.03	26.35	28.46
Total heating duty MSHSOXX	D	MWth	54.23	51.70	51.02	53.77	51.97	54.18
Total compression work MSCOMXX	E	MWe	-11.85	-10.97	-10.78	-10.51	-9.87	-11.83
Total expansion work MSTURXX	E	MWe	36.84	35.98	35.77	35.52	34.85	36.82

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Component	Parameter	Unit	11	12	13	14	15	16
Net cycle efficiency	**EFF**	**%**	**46.075**	**48.377**	**48.97**	**46.523**	**48.063**	**46.125**
Lowest boiler inlet temp.	T	°C	439.3	514.6	541.2	431.3	489.4	194.4

B.3. Partial cooling cycles (from 21 to 24)

Component	Parameter	Unit	21	22	23	24
MSCUS01 (cooler)	T1	°C	65.9	66.0	65.9	65.9
	P1	MPa	8.019	8.019	8.019	8.019
	T2	°C	33.0	33.0	33.0	33.0
	P2	MPa	7.979	7.979	7.797	7.979
	D	MWth	32.51	30.45	29.78	32.43
	M1	kg/s	200.1	187.3	183.3	199.5
MSCUS02 (cooler)	T1	°C	39.5	39.5	39.5	39.5
	P1	MPa	10.0	10.0	10.0	10.0
	T2	°C	33.0	33.0	33.0	33.0
	P2	MPa	9.950	9.950	9.950	9.950
	D	MWth	4.05	3.77	3.72	4.04
	M1	kg/s	144.2	134.3	132.5	143.8
MSCOM01 (compressor)	T1	°C	33.0	33.0	33.0	33.0
	P1	MPa	7.979	7.979	7.979	7.979
	T2	°C	39.5	39.5	39.5	39.5
	P2	MPa	10.0	10.0	10.0	10.0

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Component	Parameter	Unit	21	22	23	24
	E	MWe	0.81	0.76	0.74	0.80
	M1	kg/s	200.1	187.3	183.3	199.5
MSCOM02 (compressor)	T1	°C	33.0	33.0	33.0	33.0
	P1	MPa	9.950	9.950	9.950	9.950
	T2	°C	55.9	55.9	55.9	55.9
	P2	MPa	25.0	25.0	25.0	25.0
	E	MWe	3.47	3.23	3.19	3.46
	M1	kg/s	144.2	134.3	132.5	143.5
MSCOM03 (compressor)	T1	°C	39.5	39.5	39.5	39.5
	P1	MPa	10.0	10.0	10.0	10.0
	T2	°C	69.8	69.8	69.8	69.8
	P2	MPa	24.875	24.875	24.875	24.875
	E	MWe	1.48	1.41	1.35	1.48
	M1	kg/s	55.9	53	50.8	55.8
MSRCU01 (HTR)	T1	°C	481.9	542.5	581.8	481.6
	P1	MPa	8.10	8.10	8.10	8.10
	T2	°C	79.8	79.8	79.8	79.8
	P2	MPa	8.06	8.06	8.06	8.06
	T3	°C	69.8	69.8	69.8	69.8
	P3	MPa	24.875	24.875	24.875	24.875
	T4	°C	371.4	429.6	467.7	467.7
	P4	MPa	24.750	24.750	24.750	24.750
	D	MWth	94.54	102.05	108.58	94.21
	M1	kg/s	200.1	187.3	183.3	199.5
	M3	kg/s	200.1	187.3	183.3	157.6
MSRCU02 (LTR)	T1	°C	79.8	79.8	79.8	79.8
	P1	MPa	8.06	8.06	8.06	8.06

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Component	Parameter	Unit	21	22	23	24
	T2	°C	65.9	66.0	65.9	65.9
	P2	MPa	8.019	8.019	8.019	8.019
	T3	°C	55.9	55.9	55.9	55.9
	P3	MPa	25.0	25.0	25.0	25.0
	T4	°C	69.8	69.8	69.8	69.8
	P4	MPa	24.875	24.875	24.875	24.875
	D	MWth	4.43	4.12	4.05	4.39
	M1	kg/s	200.1	187.3	183.3	199.5
	M3	kg/s	144.2	134.3	132.5	143.8
MSHSO01 (heater)	T1	°C	371.6	429.6	467.7	69.8
	P1	MPa	24.750	24.750	24.750	24.875
	T2	°C	620.0	620.0	620.0	472.0
	P2	MPa	24.50	24.55	24.55	24.775
	D	MWth	62.21	44.66	35.03	25.05
	M1	kg/s	200.1	187.3	183.3	41.9
MSHSO02 (heater)	T1	°C	-	555.6	563.8	472.0
	P1	MPa	-	15.0	16.0	24.750
	T2	°C	-	620.0	620.0	620.0
	P2	MPa	-	14.9	15.9	24.550
	D	MWth	-	14.90	12.77	37.06
	M1	kg/s	-	187.3	183.3	199.5
MSHSO03 (heater)	T1	°C	-	-	572.2	-
	P1	MPa	-	-	11.0	-
	T2	°C	-	-	620.0	-
	P2	MPa	-	-	10.9	-
	D	MWth	-	-	10.74	-
	M1	kg/s	-	-	183.3	-

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Component	Parameter	Unit	21	22	23	24
MSTUR01 (turbine)	T1	°C	620.0	620.0	620.0	620.0
	P1	MPa	24.50	24.550	24.550	24.550
	T2	°C	481.9	555.6	563.8	481.6
	P2	MPa	8.10	15.0	16.0	8.10
	E	MWe	30.79	13.9	11.9	30.75
	M1	kg/s	200.1	187.3	183.3	199.5
MSTUR02 (turbine)	T1	°C	-	620.0	620.0	-
	P1	MPa	-	14.9	15.9	-
	T2	°C	-	542.5	572.2	-
	P2	MPa	-	8.10	11.0	-
	E	MWe	-	16.5	10.2	-
	M1	kg/s	-	187.3	183.3	-
MSTUR03 (turbine)	T1	°C	-	-	620.0	-
	P1	MPa	-	-	10.9	-
	T2	°C	-	-	571.8	-
	P2	MPa	-	-	8.10	-
	E	MWe	-	-	8.2	-
	M1	kg/s	-	-	183.3	-
Total cooling duty MSCUSXX	D	MWth	36.56	34.22	33.50	36.47
Total heating duty MSHSOXX	D	MWth	62.21	59.56	58.54	62.10
Total compression work	E	MWe	-5.76	-5.39	-5.28	-5.75

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Component	Parameter	Unit	21	22	23	24
MSCOMXX						
Total expansion work MSTURXX	E	MWe	30.79	30.39	30.32	30.75
Net cycle efficiency	**EFF**	**%**	**40.222**	**41.974**	**42.774**	**40.261**
Lowest boiler inlet temp.	T	°C	371.6	429.6	467.7	69.8

B.4. Pre-compression cycle (from 31 to 34)

Component	Parameter	Unit	31	32	33	34
MSCUS01 (cooler)	T1	°C	60.7	60.4	60.4	60.8
	P1	MPa	11.841	11.940	11.940	11.841
	T2	°C	33.0	33.0	33.0	33.0
	P2	MPa	11.781	11.880	11.880	11.781
	D	MWth	32.38	29.94	29.54	32.39
	M1	kg/s	279.4	264.4	260.6	278.3
MSCOM01 (compressor)	T1	°C	203.6	218.8	218.7	202.2
	P1	MPa	9.055	9.055	9.055	9.055
	T2	°C	236.5	253.5	253.3	235.0
	P2	MPa	11.9	12.0	12.0	11.9
	E	MWe	8.21	8.36	8.24	8.14
	M1	kg/s	279.4	264.4	260.6	278.3
MSCOM02	T1	°C	33.0	33.0	33.0	33.0

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Component	Parameter	Unit	31	32	33	34
(compressor)	P1	MPa	11.781	11.880	11.880	11.781
	T2	°C	50.7	50.5	50.5	50.7
	P2	MPa	25.0	25.0	25.0	25.0
	E	MWe	5.68	5.33	5.25	5.66
	M1	kg/s	279.4	264.4	260.6	278.3
MSRCU01 (HTR)	T1	°C	495.3	568.3	596.6	495.1
	P1	MPa	9.10	9.10	9.10	9.1
	T2	°C	203.6	218.8	218.7	202.2
	P2	MPa	9.055	9.055	9.055	9.055
	T3	°C	193.6	208.9	208.7	192.2
	P3	MPa	24.875	24.875	24.875	24.875
	T4	°C	453.9	528.0	555.4	483.4
	P4	MPa	24.750	24.750	24.750	24.750
	D	MWth	94.47	107.96	115.44	94.45
	M1	kg/s	279.4	264.4	260.6	278.3
	M3	kg/s	279.4	264.6	260.6	250.5
MSRCU02 (LTR)	T1	°C	236.5	253.5	253.3	235.0
	P1	MPa	11.9	12.0	12.0	11.9
	T2	°C	60.7	60.4	60.4	60.8
	P2	MPa	11.841	11.940	11.940	11.841
	T3	°C	50.7	50.5	50.5	50.7
	P3	MPa	25.0	25.0	25.0	25.0
	T4	°C	193.6	208.9	208.7	192.2
	P4	MPa	24.875	24.875	24.875	24.875
	D	MWth	77.89	79.72	78.52	76.96
	M1	kg/s	279.4	264.4	260.6	278.3
	M3	kg/s	279.4	264.4	260.6	278.3

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Component	Parameter	Unit	31	32	33	34
MSHSO01 (heater)	T1	°C	453.9	528.0	555.4	192.2
	P1	MPa	24.750	24.750	24.750	24.875
	T2	°C	620.0	620.0	620.0	484.0
	P2	MPa	24.50	24.550	24.550	24.775
	D	MWth	58.19	30.60	21.23	10.51
	M1	kg/s	279.4	264.4	260.6	27.8
MSHSO02 (heater)	T1	°C	-	544.3	570.8	483.5
	P1	MPa	-	13.7	16.9	24.750
	T2	°C	-	620.0	620.0	620.0
	P2	MPa	-	13.6	16.8	24.550
	D	MWth	-	24.63	15.94	47.69
	M1	kg/s	-	264.4	260.6	278.3
MSHSO03 (heater)	T1	°C	-	-	565.2	-
	P1	MPa	-	-	11.0	-
	T2	°C	-	-	620.0	-
	P2	MPa	-	-	10.9	-
	D	MWth	-	-	17.51	-
	M1	kg/s	-	-	260.6	-
MSTUR01 (turbine)	T1	°C	620.0	620.0	620.0	620.0
	P1	MPa	24.50	24.550	24.550	24.550
	T2	°C	495.3	544.3	570.8	495.1
	P2	MPa	9.1	13.7	16.9	9.100
	E	MWe	38.90	23.07	14.89	38.82
	M1	kg/s	279.4	264.4	260.6	278.3
MSTUR02 (turbine)	T1	°C	-	620.0	620.0	-
	P1	MPa	-	13.6	16.8	-
	T2	°C	-	568.3	565.2	-

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Component	Parameter	Unit	31	32	33	34
	P2	MPa	-	9.1	11.0	-
	E	MWe	-	15.59	16.58	-
	M1	kg/s	-	264.6	260.6	-
MSTUR03 (turbine)	T1	°C	-	-	620.0	-
	P1	MPa	-	-	10.9	-
	T2	°C	-	-	596.6	-
	P2	MPa	-	-	9.1	-
	E	MWe	-	-	7.02	-
	M1	kg/s	-	-	260.6	-
Total cooling duty MSCUSXX	D	MWth	32.38	29.94	29.54	32.39
Total heating duty MSHSOXX	D	MWth	58.19	55.23	54.68	58.20
Total compression work MSCOMXX	E	MWe	-13.89	-13.69	-13.49	-13.80
Total expansion work MSTURXX	E	MWe	38.90	38.66	38.49	38.82
Net cycle efficiency	**EFF**	**%**	**42.989**	**45.215**	**45.719**	**42.991**
Lowest boiler inlet temp.	T	°C	453.9	528.0	555.4	192.2

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B.5. Turbine "split-flow" cycles (from 41 to 43)

Component	Parameter	Unit	41	42	43
MSCUS01 (cooler)	T1	°C	85.0	85.1	85.0
	P1	MPa	7.860	7.860	7.860
	T2	°C	33.0	33.0	33.0
	P2	MPa	7.820	7.820	7.820
	D	MWth	40.71	36.22	40.71
	M1	kg/s	220.7	196.3	220.7
MSCOM01 (compressor)	T1	°C	33.0	33.0	33.0
	P1	MPa	7.820	7.820	7.820
	T2	°C	75.0	75.0	75.0
	P2	MPa	25.0	25.0	25.0
	E	MWe	7.17	6.37	7.17
	M1	kg/s	220.7	196.3	220.7
MSRCU01 (HTR)	T1	°C	478.4	604.6	478.2
	P1	MPa	7.90	7.9	7.9
	T2	°C	85.0	85.1	85.0
	P2	MPa	7.860	7.860	7.860
	T3	°C	75.0	75.0	75.0
	P3	MPa	25.0	25.0	25.0
	T4	°C	468.4	594.6	468.2
	P4	MPa	24.875	24.875	24.875
	D	MWth	56.61	65.63	56.61
	M1	kg/s	123.3	107.5	123.3
	M3	kg/s	97.3	88.7	97.3
MSRCU02 (LTR)	T1	°C	340.5	454.4	340.5
	P1	MPa	7.90	7.90	7.90

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Component	Parameter	Unit	41	42	43
	T2	°C	85.0	85.0	85.0
	P2	MPa	7.860	7.860	7.860
	T3	°C	75.0	75.0	75.0
	P3	MPa	25.0	25.0	25.0
	T4	°C	200.6	288.5	333.8
	P4	MPa	24.875	24.875	24.875
	D	MWth	29.08	38.21	29.08
	M1	kg/s	97.3	88.7	97.3
	M3	kg/s	123.3	107.5	70.3
MSHSO01 (heater)	T1	°C	200.6	288.5	75.0
	P1	MPa	24.875	24.875	25.0
	T2	°C	620.0	620.0	334
	P2	MPa	24.625	24.650	24.9
	D	MWth	66.11	38.21	21.91
	M1	kg/s	123.3	107.5	53.0
MSHSO02 (heater)	T1	°C	-	493.2	333.9
	P1	MPa	-	9.0	24.875
	T2	°C	-	620.0	620.0
	P2	MPa	-	8.9	24.675
	D	MWth	-	16.50	44.16
	M1	kg/s	-	107.5	123.3
MSTUR01 (turbine)	T1	°C	620.0	620.0	620.0
	P1	MPa	24.625	24.675	24.675
	T2	°C	478.4	493.2	478.2
	P2	MPa	7.9	9.0	7.9
	E	MWe	19.43	15.53	19.45
	M1	kg/s	123.3	107.5	123.3

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Component	Parameter	Unit	41	42	43
MSTUR02 (turbine)	T1	°C	468.4	620.0	468.2
	P1	MPa	24.875	8.9	24.875
	T2	°C	340.5	604.6	340.3
	P2	MPa	7.9	7.9	7.9
	E	MWe	12.73	1.92	12.71
	M1	kg/s	97.3	107.5	97.3
MSTUR03 (turbine)	T1	°C	-	594.6	-
	P1	MPa	-	24.875	-
	T2	°C	-	454.4	-
	P2	MPa	-	7.9	-
	E	MWe	-	13.93	-
	M1	kg/s	-	88.7	-
Total cooling duty MSCUSXX	D	MWth	40.71	36.22	40.67
Total heating duty MSHSOXX	D	MWth	66.11	61.26	66.06
Total compression work MSCOMXX	E	MWe	-7.71	-6.37	-7.16
Total expansion work MSTURXX	E	MWe	32.17	31.38	32.16
Net cycle efficiency	**EFF**	**%**	**37.817**	**40.811**	**37.817**
Lowest boiler inlet temp.	T	°C	200.6	288.5	75.0

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B.6. Preheating cycle (from 51 to 53)

Component	Parameter	Unit	51	52	53
MSCUS01 (cooler)	T1	°C	96.1	96.0	96.0
	P1	MPa	7.761	7.761	7.761
	T2	°C	33.0	33.0	33.0
	P2	MPa	7.722	7.722	7.722
	D	MWth	36.78	34.10	33.52
	M1	kg/s	203.5	189.6	186.4
MSCOM01 (compressor)	T1	°C	33.0	33.0	33.0
	P1	MPa	7.722	7.722	7.722
	T2	°C	86.0	86.0	86.0
	P2	MPa	25.0	25.0	25.0
	E	MWe	7.43	6.93	6.81
	M1	kg/s	203.5	189.6	186.4
MSRCU01 (HTR)	T1	°C	476.7	555.9	583.0
	P1	MPa	7.8	7.8	7.8
	T2	°C	96.1	96.0	96.0
	P2	MPa	7.761	7.761	7.761
	T3	°C	86.0	86.0	86.0
	P3	MPa	25.0	25.0	25.0
	T4	°C	467.4	546.0	573.0
	P4	MPa	24.875	24.875	24.875
	D	MWth	90.34	101.55	105.95
	M1	kg/s	203.5	189.6	186.4
	M3	kg/s	161.8	155.4	154.1
MSHSO01 (heater)	T1	°C	86.0	86.0	86.0
	P1	MPa	25.0	25.0	25.0

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Component	Parameter	Unit	51	52	53
	T2	°C	467.0	546.0	573.0
	P2	MPa	24.9	24.9	24.9
	D	MWth	23.15	19.03	22.24
	M1	kg/s	41.7	34.3	32.3
MSHSO02 (heater)	T1	°C	466.8	546.0	573.0
	P1	MPa	24.875	24.875	24.875
	T2	°C	620.0	620.0	620.0
	P2	MPa	24.675	24.675	24.675
	D	MWth	39.10	17.69	11.06
	M1	kg/s	203.5	189.6	186.4
MSHSO03 (heater)	T1	°C	-	537.2	565.5
	P1	MPa	-	13.0	16.3
	T2	°C	-	620.0	620.0
	P2	MPa	-	12.9	16.2
	D	MWth	-	19.28	12.60
	M1	kg/s	-	189.6	186.4
MSHSO04 (heater)	T1	°C	-	537.2	564.0
	P1	MPa	-	13.0	10.5
	T2	°C	-	620.0	620.0
	P2	MPa	-	12.9	10.4
	D	MWth	-	19.28	12.78
	M1	kg/s	-	189.6	186.4
MSTUR01 (turbine)	T1	°C	620.0	620.0	620.0
	P1	MPa	24.675	24.675	24.675
	T2	°C	476.7	537.2	565.6
	P2	MPa	7.8	13.0	16.3
	E	MWe	32.43	18.07	11.78

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Component	Parameter	Unit	51	52	53
	M1	kg/s	203.5	189.6	186.4
MSTUR02 (turbine)	T1	°C	-	620.0	620.0
	P1	MPa	-	12.9	16.2
	T2	°C	-	555.9	564.0
	P2	MPa	-	7.8	10.5
	E	MWe	-	13.86	12.12
	M1	kg/s	-	189.6	186.4
MSTUR03 (turbine)	T1	°C	-	-	620.0
	P1	MPa	-	-	10.4
	T2	°C	-	-	583.0
	P2	MPa	-	-	7.8
	E	MWe	-	-	7.92
	M1	kg/s	-	-	186.4
Total cooling duty MSCUSXX	D	MWth	36.59	34.10	33.52
Total heating duty MSHSOXX	D	MWth	62.25	59.38	58.68
Total compression work MSCOMXX	E	MWe	-7.43	-6.93	-6.81
Total expansion work MSTURXX	E	MWe	32.43	31.92	31.85
Net cycle efficiency	**EFF**	**%**	**40.162**	**42.102**	**42.604**
Lowest boiler inlet temp.	T	°C	86.0	86.0	86.0

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B.7. Split expansion ratio cycle (61)

Component	Parameter	Unit	Cycle 61
MSCUS01 (cooler)	T1	°C	88.9
	P1	MPa	7.960
	T2	°C	33.0
	P2	MPa	7.920
	D	MWth	37.35
	M1	kg/s	190.4
MSCOM01 (compressor)	T1	°C	33.0
	P1	MPa	7.920
	T2	°C	78.9
	P2	MPa	30.0
	E	MWe	7.51
	M1	kg/s	190.4
MSRCU01 (HTR)	T1	°C	506.5
	P1	MPa	8.0
	T2	°C	88.9
	P2	MPa	7.960
	T3	°C	78.9
	P3	MPa	30.0
	T4	°C	397.3
	P4	MPa	29.850
	D	MWth	92.76
	M1	kg/s	190.4
	M3	kg/s	190.4
MSHSO01 (heater)	T1	°C	351.8
	P1	MPa	20.0

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Component	Parameter	Unit	Cycle 61
	T2	°C	620.0
	P2	MPa	19.8
	D	MWth	63.04
	M1	kg/s	190.4
MSTUR01 (turbine)	T1	°C	397.1
	P1	MPa	29.850
	T2	°C	351.8
	P2	MPa	20.0
	E	MWe	8.23
	M1	kg/s	190.4
MSTUR02 (turbine)	T1	°C	620.0
	P1	MPa	19.8
	T2	°C	506.2
	P2	MPa	8.0
	E	MWe	24.33
	M1	kg/s	190.4
Total cooling duty MSCUSXX	D	MWth	37.33
Total heating duty MSHSOXX	D	MWth	63.04
Total compression work MSCOMXX	E	MWe	-7.51
Total expansion work MSTURXX	E	MWe	32.56
Net cycle efficiency	**EFF**	**%**	**39.731**
Lowest boiler inlet temp.	T	°C	351.8

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B.8. Basic simple recuperation Brayton cycle configuration (00)

Component	Parameter	Unit	00
MSCUS01 (cooler)	T1	°C	81.6
	P1	MPa	7.960
	T2	°C	33
	P2	MPa	7.910
	D	MWth	37.09
	M1	kg/s	200.4
MSCOM01 (compressor)	T1	°C	33
	P1	MPa	7.910
	T2	°C	71.6
	P2	MPa	25
	E	MWe	6.27
	M1	kg/s	200.4
MSRCU01 (Recuperator)	T1	°C	479.8
	P1	MPa	8
	T2	°C	81.6
	P2	MPa	7.96
	T3	°C	71.6
	P3	MPa	25
	T4	°C	370
	P4	MPa	24.875
	D	MWth	93.48
	M1	kg/s	200.4
	M3	kg/s	200.4
MSHSO01 (heater)	T1	°C	370
	P1	MPa	24.875

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Component	Parameter	Unit	00
	T2	°C	620
	P2	MPa	24.625
	D	MWth	62.73
	M1	kg/s	200.4
MSTUR01 (turbine)	T1	°C	620
	P1	MPa	24.625
	T2	°C	479.8
	P2	MPa	8
	E	MWe	31.27
	M1	kg/s	200.4
Total cooling duty MSCUSXX	D	MWth	37.09
Total heating duty MSHSOXX	D	MWth	62.73
Total compression work MSCOMXX	E	MWe	-6.27
Total expansion work MSTURXX	E	MWe	31.27
Net cycle efficiency	**EFF**	**%**	**39.85**
Lowest boiler inlet temp.	T	°C	370

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