Structural integration of the oxy-fuel power system based on exergy analysis: ASU and CPU cases

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Abstract

The oxy-combustion process has been implemented in industry for decades to improve efficiency, flexibility, emissions and the cost of many industrial systems, such as within the iron & steel and glass works. In recent years oxy-combustion has emerged as one of competitive options for CO_2 capture within several industrial processes.

The current paper has been prepared within the O2GEN project, which is co-financed by the European Union and coordinated by CIRCE – The Research Centre for Energy Resources and Consumption from Spain. The objective is to demonstrate the concept of the second generation oxy-fuel combustion process which reduces significantly the overall efficiency penalty of CO_2 capture in power plants.

The diagnosis and evaluation of potential for improvement of oxy-fuel process efficiency has been performed using the exergy analysis. Exergy is a measure of the quality of energy. It expresses the maximum work output attainable in natural environment or a minimum work input necessary to realize the reverse processes. The exergy analysis detects the possible thermodynamic improvements of thermal and chemical processes. The dedicated exergy analysis tool for evaluation of oxy-fuel plant energy structure has been developed.

The calculation results indicated the air separation unit (ASU) as one of crucial components of an oxy-fuel system in terms of integration and optimization potential. Production of high-purity oxygen for the combustion process is related to substantial electricity consumption for compression processes necessary for cryogenic separation. On the other hand, ASU compressors require intensive cooling to keep the electricity consumption on possibly low level. Substantial amount of waste heat is therefore available for other parts of the oxy-fuel system. The optimal ASU and overall oxy-fuel system integration seems to be one of crucial ways of increasing the final efficiency of electricity generation. Another issues influencing the efficiency and in some sense related to ASU operation are oxygen preheating and oxygen content in oxidizer supplied to the combustion chamber of the steam boiler.

The O2GEN project partners: VTT, Air Liquide and SUT have been working together and studied the exergy effectiveness of the main blocks within oxy-combustion power generation system: CFB (Circulated Fluidized Bed) boiler, ASU and CPU (CO_2 processing unit), as well as their integration and the possible improvements.

Thermodynamic analysis connected to detailed simulation modelling of abovementioned improvements has determined the potential for efficiency increase related to oxidizer production and utilization within the oxy-fuel system.

VTT, Technical Research Centre of Finland has developed a dynamic CFB boiler model. SUT has prepared simulation models for the overall oxy-fuel power units using the AspenPlus and Thermoflex software, as well as prepared the dedicated exergy analysis tool. Air Liquide has been a key contributor to the ASU (Air Separation Unit) and the Cryocap™ Oxy which represent the largest share of Capex and Opex costs of CO_2 capture.

The paper is first describing the exergy performance of each block of the reference oxy-combustion system including: boiler, steam cycle, ASU and Cryocap™ Oxy. The paper is then presenting improvements which could be achieved by the 2015-2020 timeframe to decrease the energy cost associated with CO_2 capture. It includes near/mid-term developments in ASU and Cryocap™ Oxy process designs.

As a conclusion, the design of the second generation oxy-fuel power generation system and its energy performance is presented.

1. Introduction

Air separation unit (ASU) is one of crucial components of an oxy-fuel system. Production of high-purity oxygen for the combustion process is however, related to substantial electricity consumption for compression processes necessary for cryogenic separation. On the other hand, ASU compressors require intensive cooling to keep the electricity consumption on the nearest low level. Substantial amount of waste heat is therefore available for other parts of the oxy-fuel system. The optimal ASU and overall oxy-fuel system integration seems to be one of crucial ways of increasing the final efficiency of electricity generation. Another issues influencing the efficiency and related to ASU operation are oxygen preheating and oxygen content in the oxidizer supplied to the furnace of the boiler.

Thermodynamic analysis of abovementioned improvements will determine the potential for efficiency increase related to oxidizer production and utilization within the oxy-fuel system. The analysis has been started from definition of reference oxy-fuel case, which is a non-integrated plant, representing the current state of technology. This case is called *1st-gen oxy-fuel* plant, while the corresponding air-fired CFB plant, which was used for steam cycle and boiler technology determination, is called *air-fired reference*. Both the air-fired and 1st-gen oxy-fuel reference plants parameters have been defined based on project partners experience and previously executed research.

The idea of ASU-related improvements was to examine each of them separately, then integrate the most promising ones into one system and finally, determine the sensitivity of the final integrated case to ambient and fuel parameters.

2 Definition of reference power systems

The reference power systems are used for purposes of comparison and assessment of feasibility of the proposed oxy-fuel cycle improvements. One of the most important assumptions valid for all the modelling and simulation processes is that the parameters which are beyond the scope of analyzed improvements, assume values as in the 1st-gen oxy-fuel reference. Similarly, the parameters of 1st-gen oxy-fuel system, which are not specific for oxy-combustion technology, are kept at the level of that in the air-fired reference case.

2.1 Reference air-fired power unit

Reference air-fired power unit is based on current state of supercritical CFB technology as presented at several real installations. The reference plant has been presented in Fig. 2.1 and consists of:

- supercritical CFB boiler,
- steam turbine (high, medium and two low-pressure parts),
- three low-pressure regeneration heat exchangers,
- three high-pressure regeneration heat exchangers,
- steam desuperheater,
- steam-driven boiler-feed water pump,
- wet, natural draft cooling tower,
- electrostatic precipitator,
- low-temperature heat recovery system.

Detailed description of assumed reference plant parameters have been presented in section 3.2.

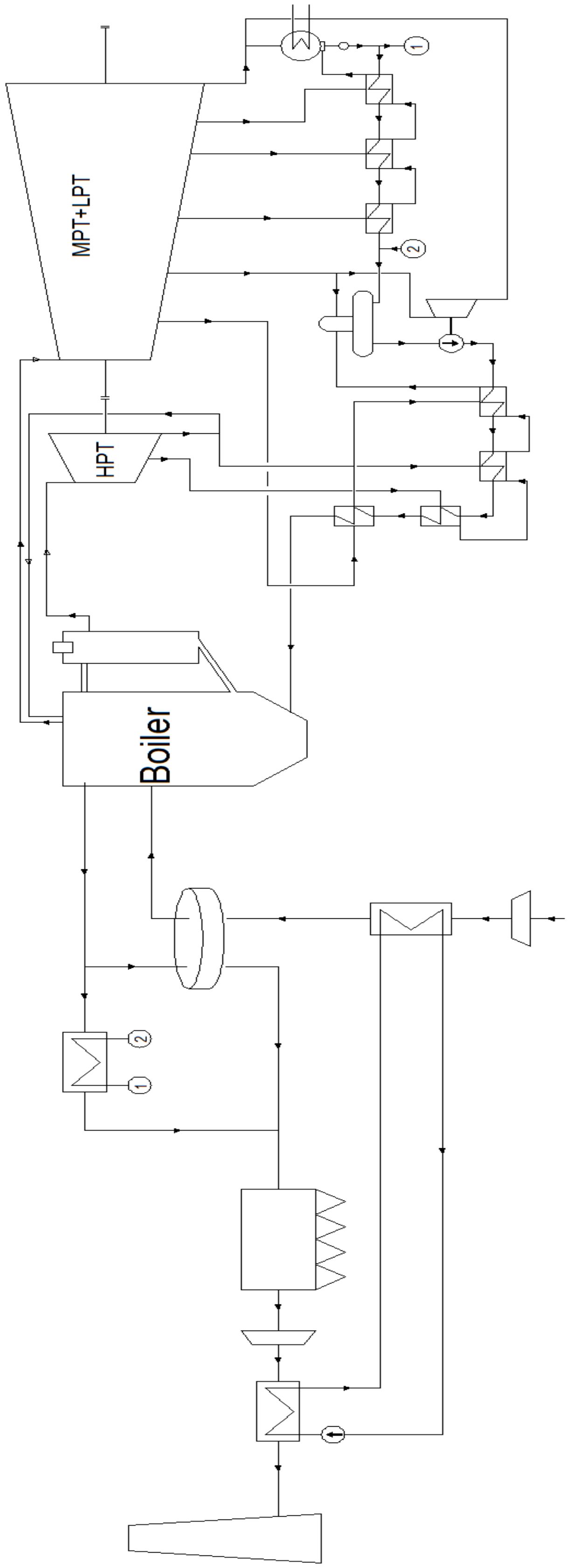

Fig. 2.1 Scheme of air-fired reference power unit

2.2 Reference 1^{st}-gen oxy-fuel plant

Schematic diagram of reference 1^{st}-gen oxy-fuel plant has been presented in Fig. 2.2. It has been created starting from the air-fired reference plant. Main changes took place within the boiler island, while steam cycle has been kept unchanged. Low-temperature heat recovery system has been cut-off. Within the boiler island, the changes include introduction of the recirculation loop of the flue gas and replacing of rotary air preheater by rotary regenerative heat exchanger allowing for rational flue gas cooling before the electrostatic precipitator, where the required temperature is equal to 145 ^{o}C. Finally, to reach this value, the flue gas is additionally cooled down by condensate taken from the steam cycle. Moreover, two additional installations have been added into the plant structure – ASU and CPU (Compression and Purification Unit). Conceptual design and parameters of both of these subsystems have been provided by Air Liquide. Both the ASU and CPU are of cryogenic type and include necessary compressors, heat exchangers and separation devices. The CPU is based on Air Liquide Cryocap^{TM} Oxy design.

Detailed description of the parameters of the 1^{st}-gen oxy-fuel reference plant has been presented in section 3.1.

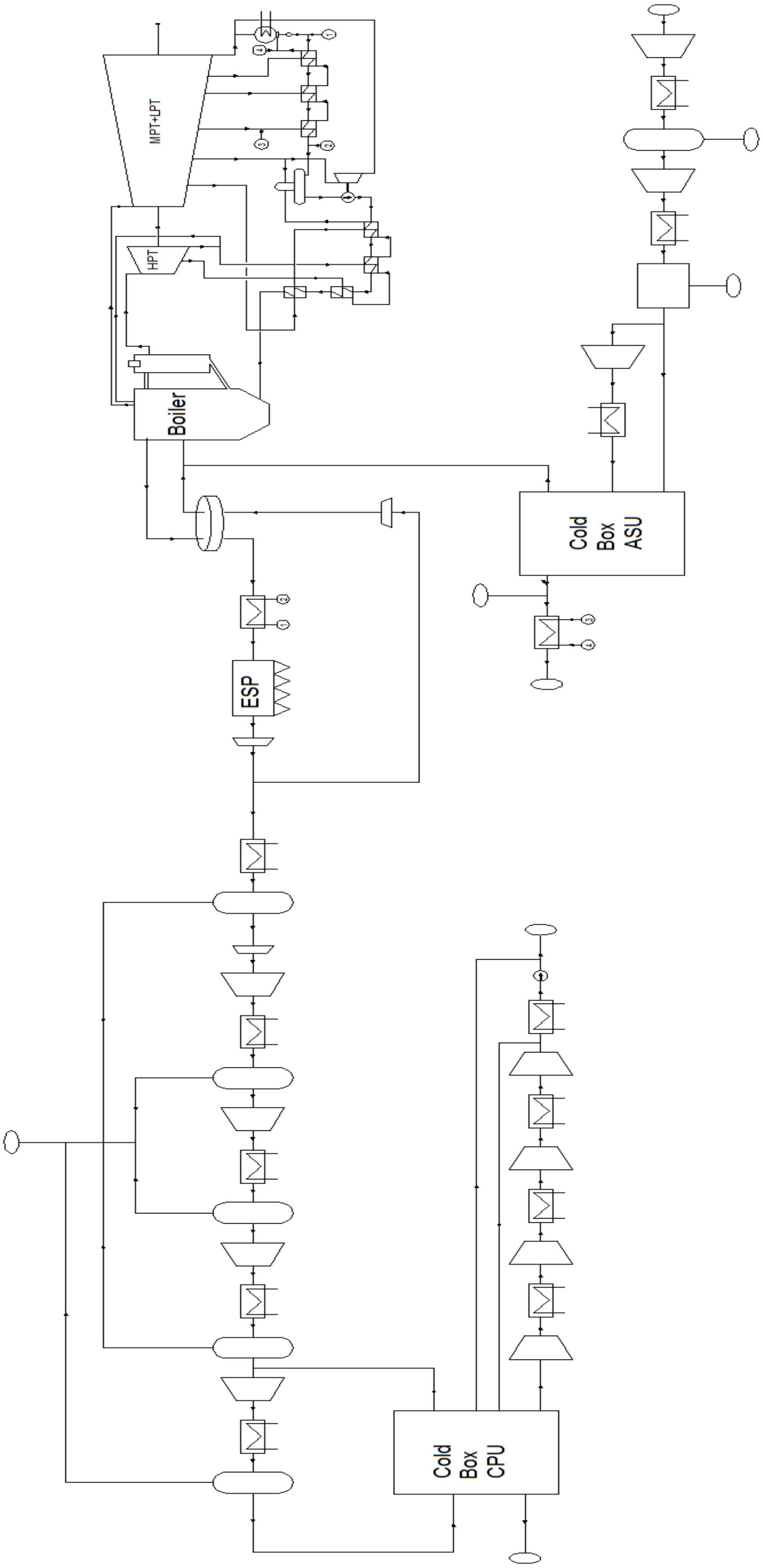

Fig.2.2 Scheme of 1st-gen oxy-fuel reference plant

3 Simulation modeling of reference plants

3.1 Key model input data and hypothesis

Simulation models of reference plants have been based on boiler and steam turbine diagrams presented in section 2, as well as, assumptions presented in Tables 3.1 - 3.3. The shape of this configuration has been based on current state of supercritical plants technology using best practice engineering. The simulation models of the boiler, steam cycle, ASU and CPU islands have been prepared on the Thermoflex software. Additionally ASU and CPU have been modelled on AspenPlus software for detail verification of cold box balances and two-phase flow parameters.

Table 3.1 Coal parameters

Coal parameters (as received)		
Moisture	%	7,81
Ash	%	21,9
Carbon	%	62,27
Hydrogen	%	2,259
Nitrogen	%	1,097
Chlorine	%	0,0184
Sulfur	%	2,406
Oxygen	%	2,24
LHV	kJ/kg	23395
HHV	kJ/kg	24079

Table 3.2 Parameters for simulation models common for air-fired and 1st-gen oxy-fuel reference plants

Parameter	Unit	Value
Live steam temperature	ºC	600
Live steam pressure	bar	250
Reheated steam temperature	ºC	610
Reheated steam pressure	bar	54
Boiler feed-water temperature	ºC	299
Boiler feed-water pressure	bar	298,4
Boiler feed-water mass flow	kg/s	512,8
Ambient air pressure	mbar	950
Ambient air temperature	ºC	12,6
Ambient air relative humidity	%	66
Cooling water temperature	ºC	20
Turbine condenser pressure	mbar	50
HP turbine isentropic efficiency of stages	%	90,8-96,2
MP turbine isentropic efficiency of stages	%	78,9-90
LP turbine isentropic efficiency of stages	%	85,7-94,35

Table 3.3 Assumptions for simulation model of 1st-gen oxy-fuel reference plant

Parameter	Unit	Value
Oxygen purity at ASU exit	%vol	96,6
Temperature pinch in compressors intercoolers	K	5
Polytrophic efficiency of ASU compressors	%	87
Polytrophic efficiency of CPU compressors	%	86

3.2 Results

Key parameters obtained from simulation models of both reference power units have been presented in Table 3.3.

Table 3.3 Results of modeling of reference power units

Parameter	Unit	Air-fired reference	1st-gen oxy-fuel reference
Gross electric power	MW	705,7	690,3
Gross electric efficiency	%	45,59	44,58
Net electric power	MW	672,5	512,8
Net electric efficiency	%	43,45	33,11
Fuel flow rate	kg/s	66,16	66,19
Fuel LHV	kJ/kg	23395	23395
Oxygen flow rate	kg/s	-	127,5
Pure oxygen flow rate	kg/s	-	123,2
ASU gross power consumption	MW	-	91,32
ASU specific gross power consumption per ton of pure oxygen*	MJ/kg	-	0,7414
ASU specific net power consumption per ton of pure oxygen**	MJ/kg	-	0,753

* ASU specific gross power consumption: ASU electrical consumption per ton of pure oxygen

** ASU specific net power consumption: “ASU net electrical consumption” per ton of pure oxygen, where the “ASU net electrical consumption” is the ASU electricity requirement, plus the ASU steam consumption electricity equivalent, minus the steam cycle additional electricity output generated by ASU heat integration

4 Exergy analysis of 1st-gen oxy-fuel plant

Exergy is a measure of the quality of energy. It expresses the maximum work output attainable in natural environment or a minimum work input necessary to realize the reverse process. The exergy analysis detects the possible thermodynamic improvements of thermal and chemical processes.

The exergy balance for each device of oxy-fuel plant may be set up. Figure 4.1 presents such an exergy balance for one subsystem. Exergy does not satisfy the law of conservation, so that the exergy balance must be closed by the internal exergy losses (exergy destruction). The exergy balance performed within current work takes into account usable exergy input of all energy carriers supplied to the considered device and usable exergy output of these energy carriers, which are delivered to other devices. The loss of exergy is the sum of the internal loss and exergy loss associated with the energy carriers leaving the unit (waste products) which are no longer used in the system. Internal exergy losses determined in compliance with Gouy-Stodola's law are irretrievable and cannot be even partly recovered. Every exergy loss contributes to an increased consumption of input energy in the process or to a decrease of its useful effects.

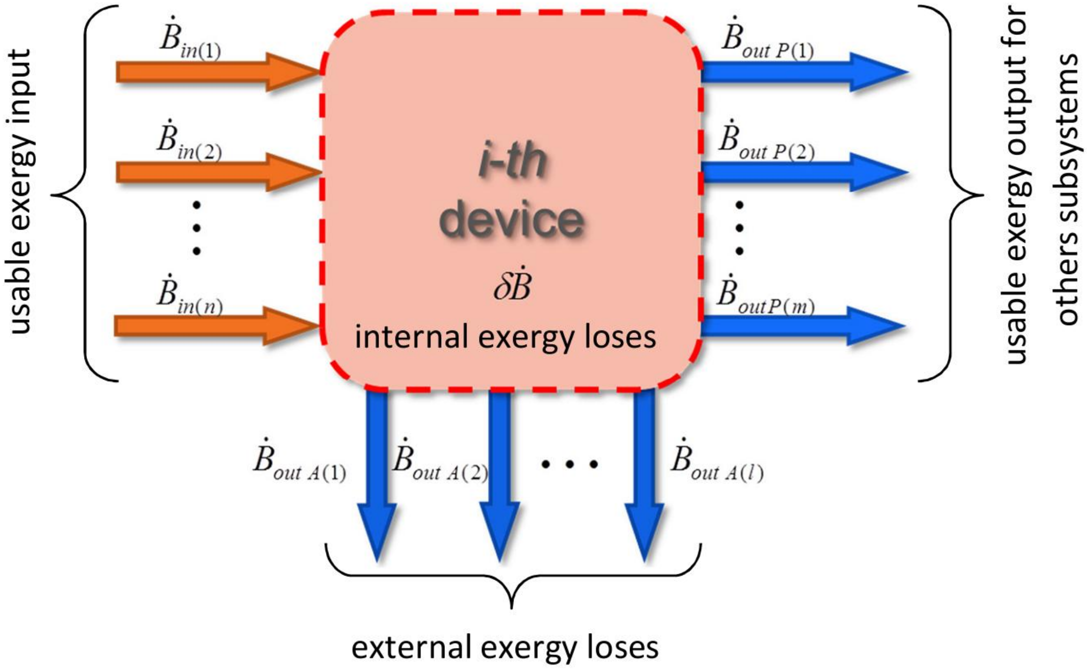

Fig. 4.1. Exergy balance of one analyzed device/subsystem

The exergy balance performed is expressed by following relations:

-internal exergy losses:

$$\delta\dot{B} = \dot{B}_{in} - \dot{B}_{out} \tag{4.1}$$

-sum of external exergy output:

$$\dot{B}_{out} = \dot{B}_{out\ P} + \dot{B}_{out\ A} \tag{4.2}$$

-sum of internal and external exergy losses:

$$\Delta\dot{B} = \delta\dot{B} + \dot{B}_{out\,A} = \dot{B}_{in} - \dot{B}_{out\,P} \tag{4.3}$$

Relative exergy losses:

$$\zeta_i = \frac{\Delta\dot{B}}{\dot{B}_{fuel}} \cdot 100\% \tag{4.4}$$

where $\dot{B}_{fuel}$ represents exergy of input fuel.

Exergy of a stream of matter crossing a system boundary is a principal quantity appearing in exergy balances. This quantity can be divided into two most important components: physical exergy b_f and chemical exergy b_{ch}.
The total exergy flow rate is expressed as:

$$\dot{B} = \dot{m}\left(b_f + b_{ch}\right) \tag{4.5}$$

where $\dot{m}$ denotes flow rate of substance.

Physical exergy is calculated from the state determined by the ambient temperature T_a and pressure p_a:

$$b_f = h - h_a - T_a \cdot \left(s - s_a\right) \tag{4.6}$$

where h and s denotes specific enthalpy and entropy.

Chemical exergy expresses the exergy content of the substance at environmental temperature and pressure. Its value results from the difference of composition of this substance in relation to the commonly appearing components of the environment. In general, the chemical exergy is estimated using thermodynamic tables storing standard chemical exergy $b_{ch\,n}$. The chemical exergy is calculated from the following formula:

$$b_{ch} = \sum_i g_i \left(b_{chn\,i} + RT_a \ln z_i\right) \tag{4.7}$$

where z_i and g_i denote mole and mass fraction of the ith component

The chemical exergy of gas fuels can be determined by means of standard chemical exergy. This technique cannot, however, be used for most of solid and liquid organic fuels consisting of complex solutions and mixtures of many unknown components. An approximate calculation method proposed by Szargut [1] is based on an analogy with the chemical exergy of organic pure substances:

$$\dot{B}_{fuel} = \dot{m} \cdot b_{ch\,fuel} \tag{4.8}$$

where:

$$b_{ch\,fuel} = \left(LHV_{fuel} + rw\right)\beta + \left(b_{chS} - LHV_S\right)s + b_{ch\,p}\,p + b_{chw}\,w \tag{4.9}$$

and r denotes enthalpy of vaporization.

$$\beta = 1.040 + 0.1728\frac{h}{c} + 0.0432\frac{o}{c} + 0.2169\frac{s}{c}\left(1 - 2.0628\frac{h}{c}\right) \tag{4.10}$$

where h, o, s, p, w denote ratio of elements of hydrogen, oxygen, sulfur, ash and water fraction.

For the exergy analysis the whole flowchart of the 1st-gen oxy-fuel plant has been divided into following subsystems:

- boiler island
- steam island
- air separation unit (ASU)
- CO_2 processing unit (CPU)

Figure 4.2 presents the flowchart with the applied control volume boundaries for the exergy analysis. Table 4.1 shows the calculated exergy losses for each considered subsystem.

Table 4.1. Exergy losses for each selected subsystem of the 1st-gen oxy-fuel reference plant

Process unit	, kW
STEAM ISLAND	120692
BOILER	820142
CPU	40089
ASU	104440

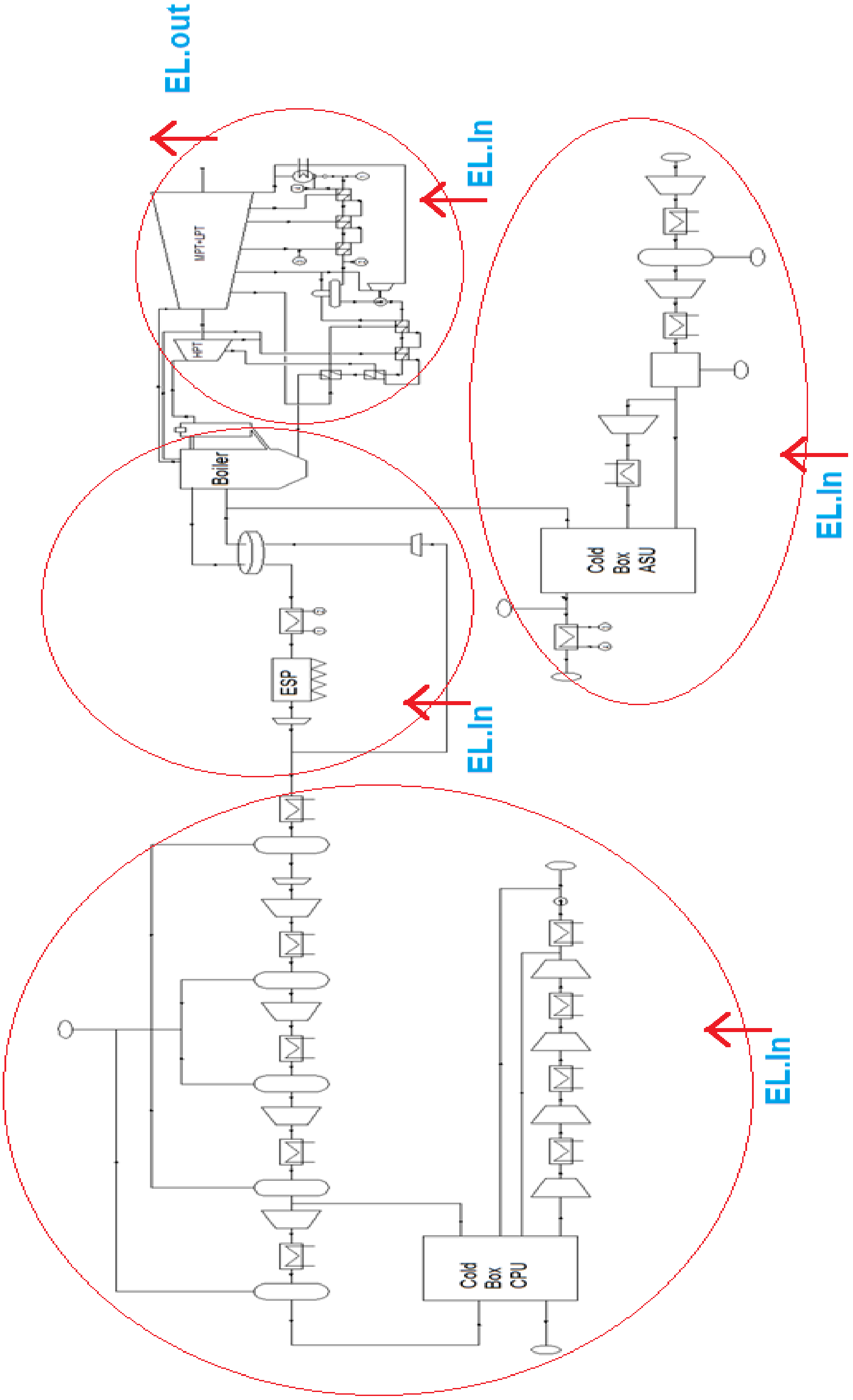

Fig. 4.2. Control volume boundaries for exergy analysis of 1st-gen oxy-fuel reference plant

As it is presented in Fig. 4.3 and Fig. 4.4, the boiler is responsible for the highest exergy loses in the analyzed system.

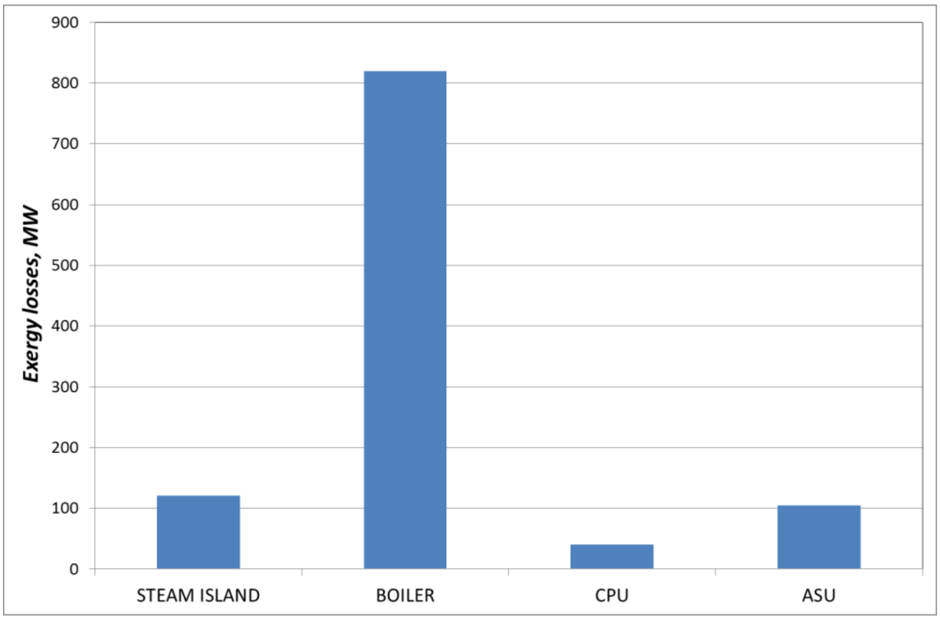

Fig. 4.3. Exergy losses for considered subsystems of the 1st-gen oxy-fuel reference plant

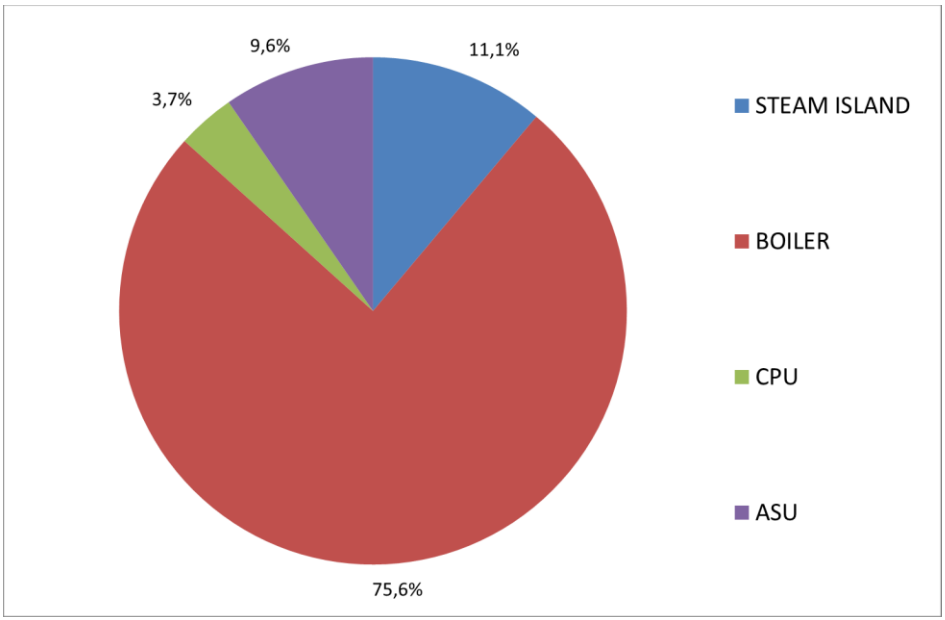

Fig. 4.4. Share of exergy losses for the considered subsystems of the 1st-gen oxy-fuel reference plant

The calculated overall gross exergy efficiency of the entire 1st-gen oxy-fuel reference plant is equal $\eta_{ex\,gross} = 42.57\%$ while net plant exergy efficiency $\eta_{ex\,net} = 32.34\%$. The exergy efficiency of ASU unit (generated nitrogen is considered as a waste) equals to $\eta_{ASU\ ex} = 18.55\%$. Relative exergy losses and exergy efficiency should sum up to 100%. In this analysis $\sum \zeta_i + \eta_{ex\,net} = 100.07\%$, the inaccuracy is equal 0.7% and probably results from approximate value of the chemical fuel exergy.

5 ASU integration concepts and analysis

The main goal of the presented work is to reduce the efficiency penalty caused by oxy-fuel combustion. To obtain this target, several improvements related to ASU integration and oxygen enrichment of the oxidizer supplied to boiler burners have been defined and examined. The ideas of considered modifications are presented in table 5.1. All the cases are calculated on the base of reference 1st-gen oxy-fuel plant. Each of cases 1 – 4 introduce only one type of change. Based on the results obtained for cases 1 - 4, the final case 5 has been developed. It integrates the improvements with the highest potential for net efficiency increase. Schematic thermal flowcharts have been developed for defined improvement cases as presented in following subsections. Red lines represent the ideas of changes compared to the 1st-gen reference plant.

Table 5.1 List of analyzed improvement cases

case 1	2-stage intercooled ASU air compressor and heat integration
case 1a	2-stage intercooled ASU air compressor and heat integration + final cooling
case 2	1-stage adiabatic ASU air compressor and heat integration
case 2a	1-stage adiabatic ASU air compressors and heat integration + final cooling + increased preheated water temperature (171 ^{o}C)
case 3	oxygen preheating by steam
case 3a	oxygen preheating by flue gas
case 4	oxygen content in oxidizer increased to 40 %
case 5	integration of improvements of cases 2a, 3a and 4

5.1 Case 1: 2-stage intercooled ASU air compressor and heat integration

The idea of Case 1, as illustrated in Fig. 5.1, is heat recovery from inter-stage air coolers installed within ASU main air compressor into steam cycle condensate. Condensate preheating enables for decreasing of the steam flow rate to appropriate regenerative heaters within steam cycle, and therefore for increasing of the of turbine power. In case 1, the condensate replaces the cooling water, which means that the compressed air is not cooled to the same temperature as in reference case. This increases the compressor power consumption. Case 1a (Fig. 5.2) has been formulated to eliminate this drawback. The difference is in final cooling of air before entering the next stage of compression – final coolers remain unchanged (same as in reference case), while condensate regenerative heat exchangers are the same as in case 1. This change should increase the net electricity production within the whole system.

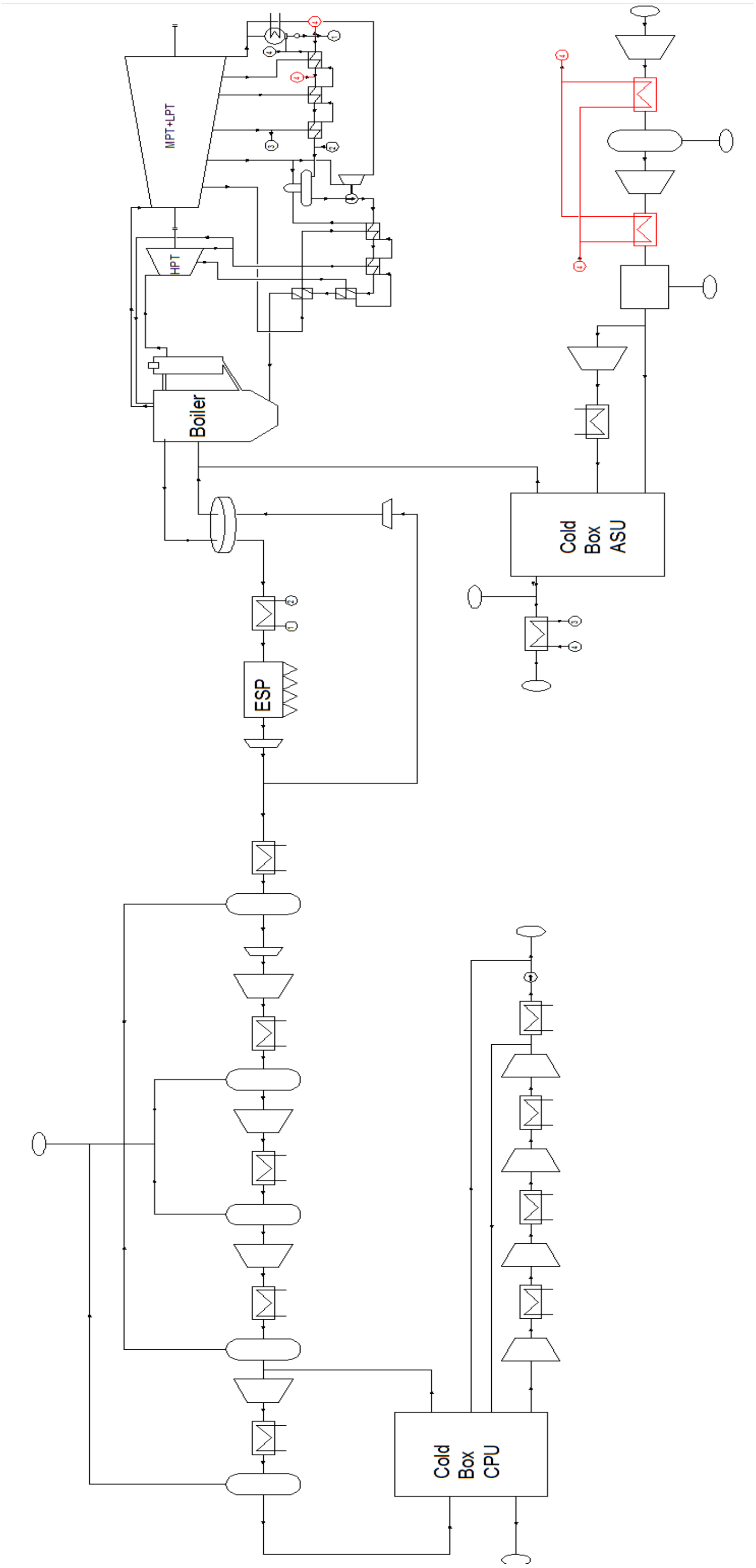

Fig. 5.1 Scheme of case 1 improvement

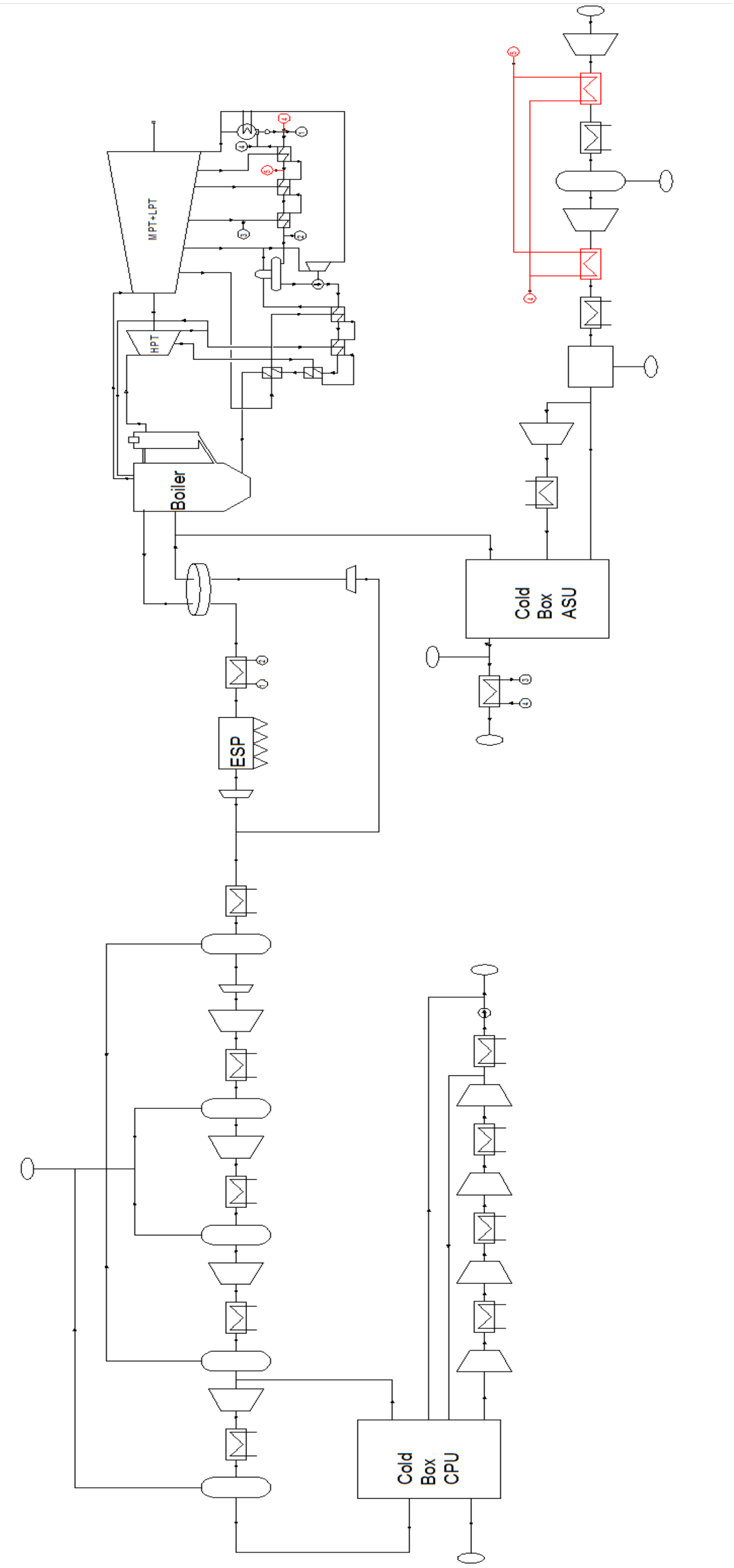

Fig. 5.2 Scheme of case 1a improvement

5.2 Case 2: 1-stage adiabatic ASU air compressor and heat integration

The idea of case 2 modification is to use adiabatic ASU main air compressor with final cooler instead of intercooled machine. Heat recovery from final air cooler into steam cycle is then possible at higher temperatures when compared with cases 1 and 1a. Moreover, it is possible to obtain higher polytrophic efficiencies of the compression stages. It has been assumed that the polytrophic efficiency of adiabatic compressor is equal to 90% comparing to 87% for reference case. This assumption is based on the use of axial compressor technology instead of centrifugal integrally geared technology. Axial compressors have slightly higher stage efficiency than centrifugal compressors but cannot be used for inter-cooled compression because the geometry is not adapted. The difference between case 2a and 2 is in the installation of the final cooling of air to a temperature of 25 ^{o}C before entering the ASU main heat exchanger and final stage of compression. Heat from recovery system is transferred to steam cycle condensate. Condensate preheating decreases the steam flow rate to appropriate regenerative heaters within steam cycle and therefore leads to an increase of turbine power.

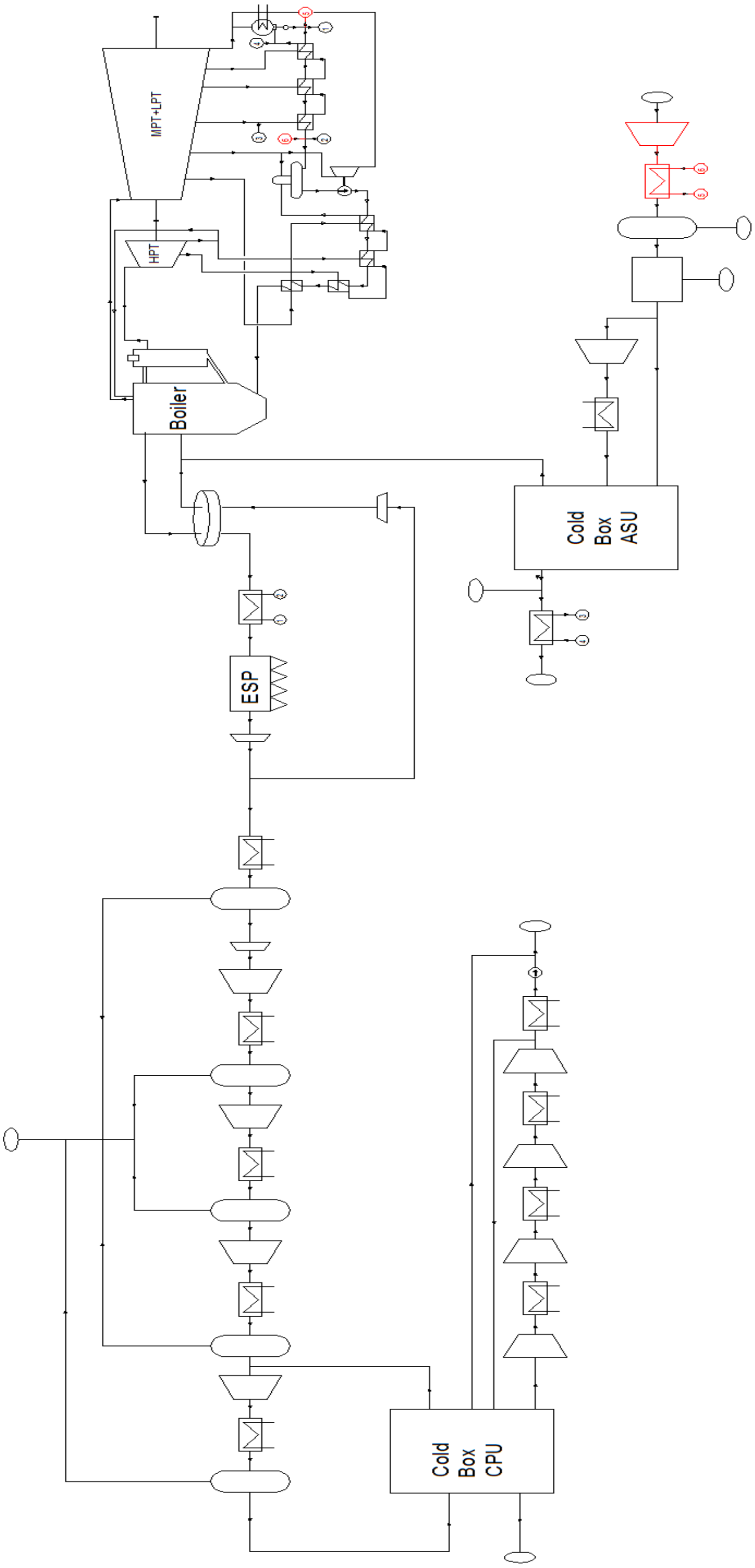

Fig. 5.3 Scheme of case 2 improvement

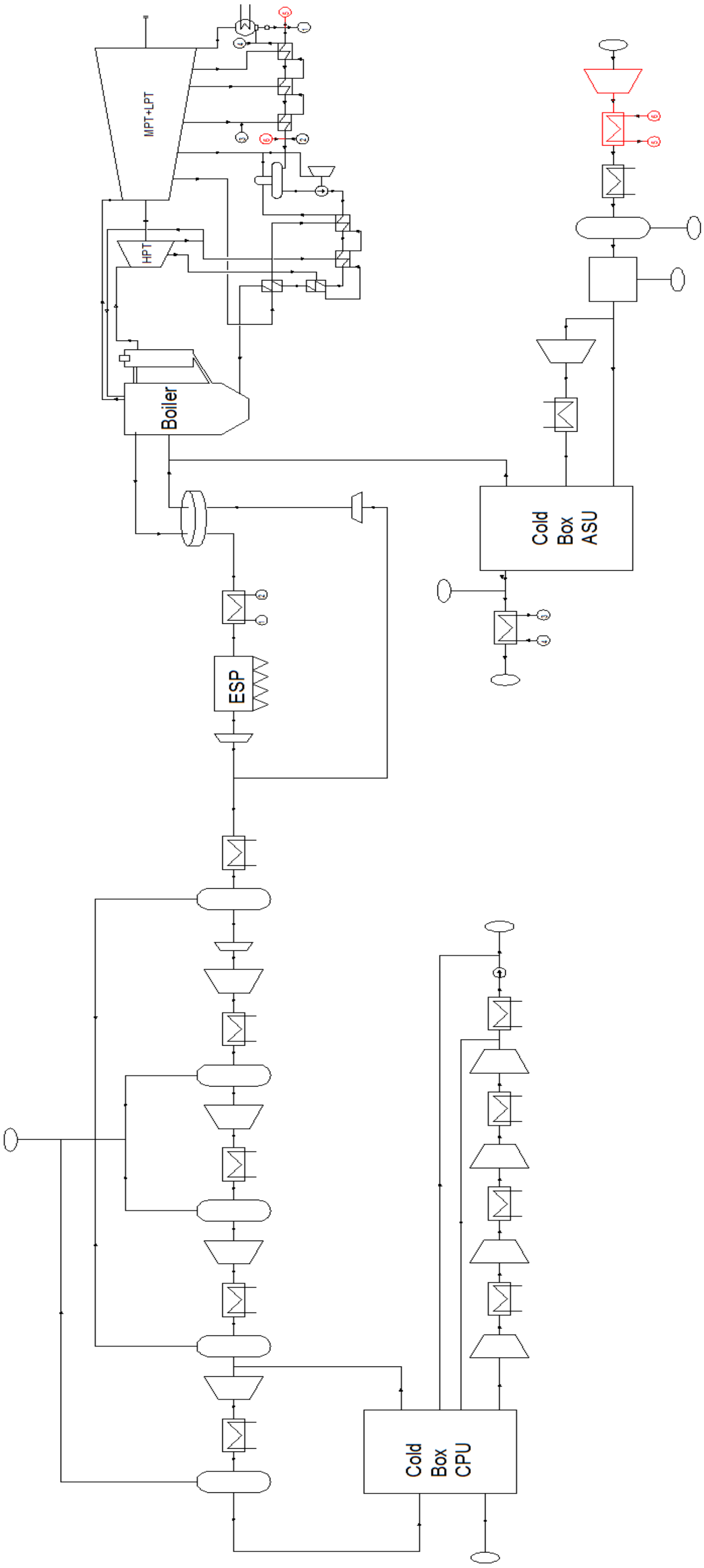

Fig. 5.4 Scheme of case 2a improvement

5.3 Case 3: oxygen preheating

The change introduced in case 3 is oxygen preheating before it is mixed with the recirculated flue gas entering boilers as oxidizer. Combustion oxygen is preheated to 300 ^{o}C. In both 3 (Fig. 5.5) and 3a (Fig. 5.6) cases, the first stage of oxygen preheating is performed by flue gas leaving the recirculation loop, before it enters the CPU island. The second stage of preheating is realized by steam extracted from HP turbine (case 3) or by flue gas extracted from boiler before the rotary heater (case 3a). Oxygen preheating represents typical heat recuperation within the combustion process and is comparable to air preheating in conventional boilers. One of the barriers for practical implementation may be however, the capital cost of gas-gas heaters, as well as, safety issues related to oxygen in-leakage to flue gas.

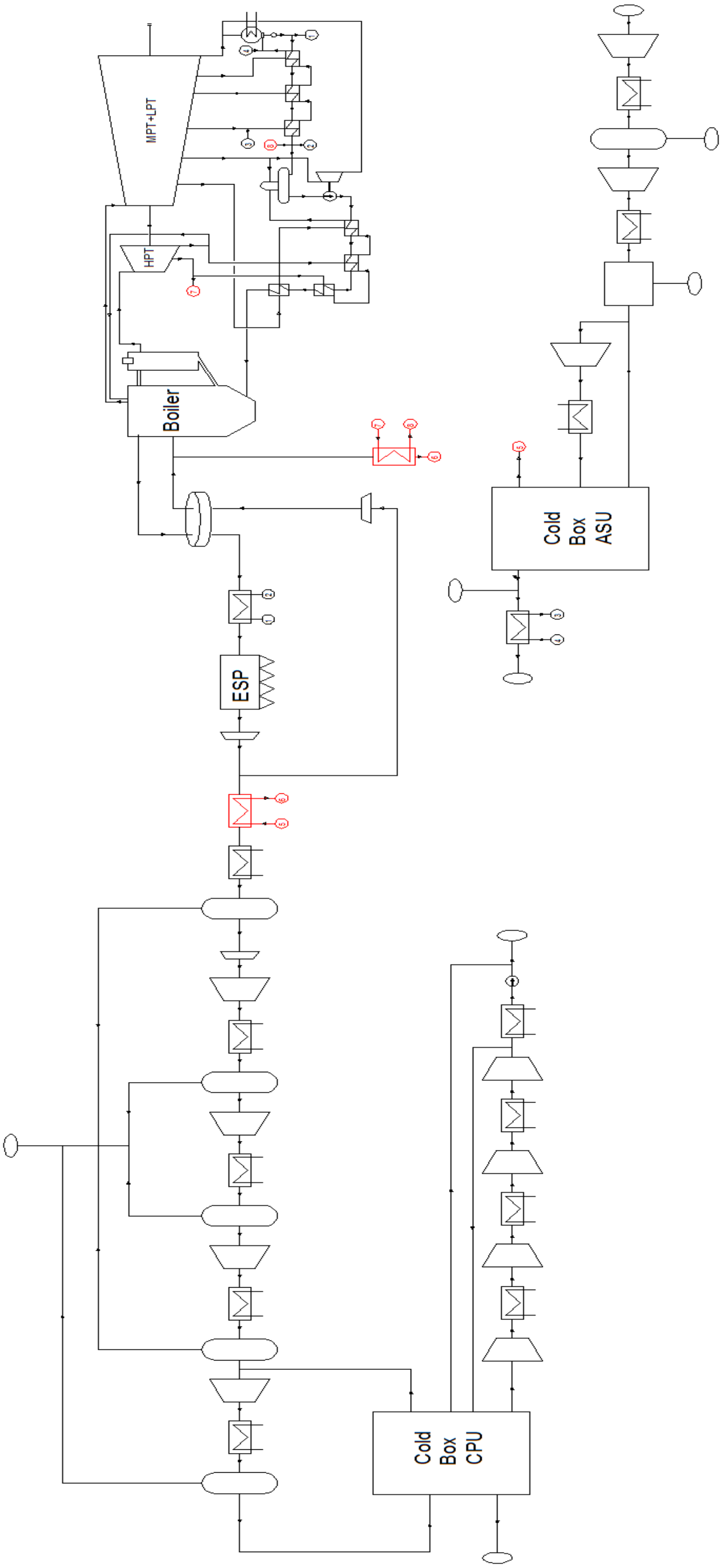

Fig. 5.5 Scheme of case 3 improvement

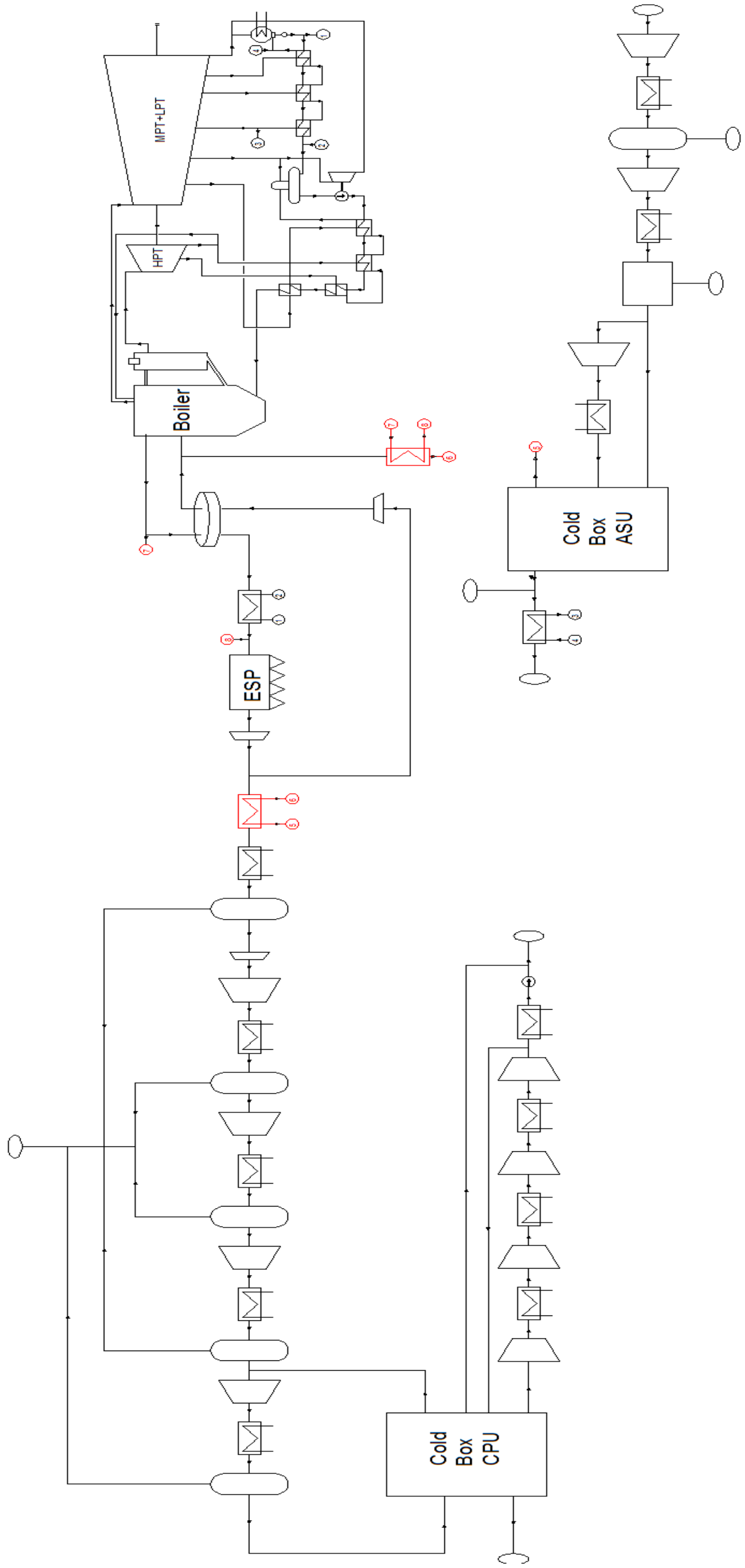

Fig. 5.6 Scheme of case 3a improvement

5.4 Case 4: increased oxygen content in oxidizer

Case 4 considers higher oxygen content in oxidizer going to the combustion process than in the reference plant. The mole fraction of O_2 in the oxidizing gas has been increased to 40 % (from 26,5% for 1st-gen oxy-fuel plant). Increase of oxygen content influences the temperatures in the boiler and as a result, the temperature at the outlet of the cyclone reaches 923 ^{o}C. (850 ^{o}C for the1st-gen oxy-fuel plant). Flue gas temperature increase is related to lower amount of inert gas supplied to furnace through flue gas recirculation loop. There are no changes to the flowchart of the plant, so case 4 configuration is the same as shown in Fig. 2.2.

5.5 Case 5: integration of improvements of cases 2, 3 and 4

Case 5 represents the integration of the improvements analyzed within cases 2a, 3a and 4. Its thermal diagram has been presented in Fig. 5.7.

5.6 Results

Key results of simulation modelling for cases 1-5 have been collected in Table 5.2.

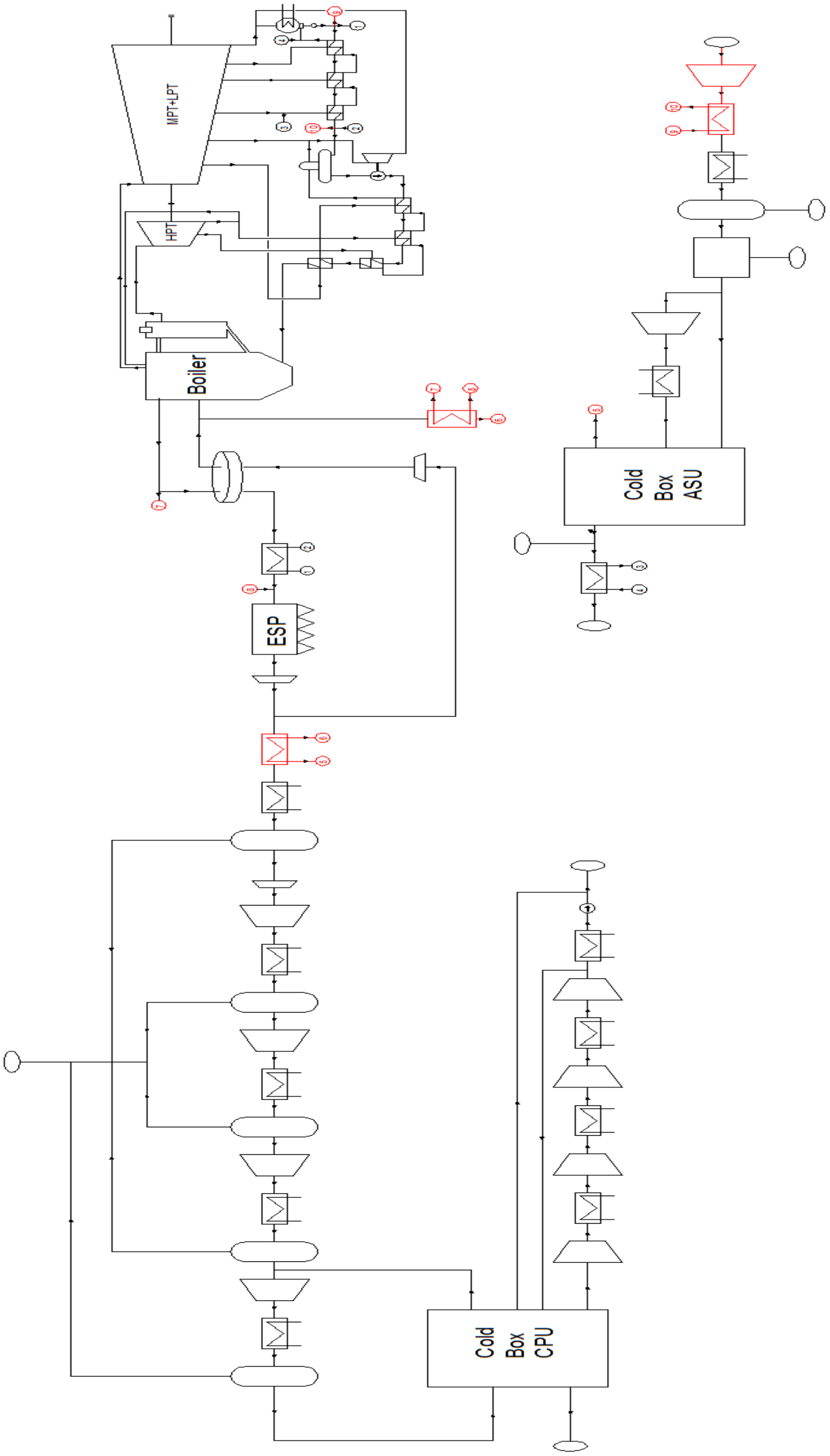

Fig. 5.7 Scheme of case 5 improvements

Table 5.2 Results of simulation modelling for cases 1-5

Parameter	Unit	oxy-fuel cases							
		case 1	case 1a	case 2	case 2a	case 3	case 3a	case 4	case 5
Gross electric power	MW	694,4	694,5	705,4	706,1	701,5	706,98	703,5	734,1
Gross electric efficiency	%	44,84	44,85	45,55	45,6	45,32	45,68	45,45	47,43
Net electric power	MW	509,5	514,1	522	522,9	523,6	529	528,9	553,3
Net electric efficiency	%	32,9	33,2	33,71	33,77	33,83	34,18	34,17	35,74
Fuel mass flow rate	kg/s	66,19	66,19	66,19	66,19	66,16	66,16	66,16	66,16
Fuel LHV	kJ/kg	23395	23395	23395	23395	23395	23395	23395	23395
Oxygen flow rate	kg/s	127,5	127,5	127,5	127,5	127,4	127,4	129,4	129,5
Pure oxygen flow rate	kg/s	123,2	123,2	123,2	123,2	123,1	123,1	125,0	125,1
ASU gross power consumption	MW	98,33	93,83	96,40	96,16	91,27	91,27	92,76	97,68
ASU specific gross power consumption per ton of pure oxygen	MJ/kg	0,7983	0,7618	0,7827	0,7807	0,7416	0,7416	0,7421	0,7808
ASU specific net power consumption per ton of pure oxygen	MJ/kg	0,777	0,739	0,672	0,664	0,753	0,753	0,754	0,665

6 Sensitivity analysis

Sensitivity analysis of the calculated parameters of the oxy-fuel system with respect to changes of ambient, fuel and design steam parameters has been performed. Case 5 have been chosen as a base for the sensitivity calculations. Tables 6.1 -6.3 summarizes scenarios assumed for evaluation of the sensitivity. The methodology was each time the same – starting from case 5 settings, some of them have been modified as shown in Tables 6.2 and 6.3, but the remaining parameters and assumptions were kept unchanged. All changes of input data have been implemented in the design mode of power unit operation, so the sensitivity cases should be treated as new, reconstructed plants. Calculated parameters of oxy-fuel plants for determined sensitivity cases have been collected in Table 6.4.

Table 6.1 Sensitivity analysis cases

	Sensitivity cases description
s 1	different ambient conditions
s 2	different cooling water condition
s 3	different steam parameters
s 4	different fuel

Table 6.2 Sensitivity analysis - main assumptions within sensitivity cases

Parameter	Unit	Value				
		case 5	s1	s2	s3	s4
Live steam temperature	ºC	600	600	600	700	600
Live steam pressure	bar	250	250	250	300	250
Reheated steam temperature	ºC	610	610	610	701	610
Reheated steam pressure	bar	54	54	54	54	54
Boiler feed water temperature	ºC	298,6	298,6	298,6	300	298,6
Boiler feed water pressure	bar	298,4	298,4	298,4	345	298,4
Boiler feed water mass flow	kg/s	542,7	542,7	542,7	482,8	496,6
Ambient air pressure	mbar	950	950	950	950	950
Ambient temperature	ºC	12,6	28,8	12,6	12,6	12,6
Ambient air relative humidity	%	66	24	66	66	66
Cooling water temperature	ºC	20	26,28	25	20	20
Turbine condenser pressure	mbar	50	72	66	50	50

Table 6.3 Coal parameters for the sensitivity analysis

Coal parameters (as received)		case 5 and s1-s3	s4
Moisture	%	7,81	15
Ash	%	21,9	11,05
Carbon	%	62,27	55,76
Hydrogen	%	2,259	3,74
Nitrogen	%	1,097	0,9265
Chlorine	%	0,0184	0
Sulfur	%	2,406	1,717
Oxygen	%	2,24	11,81
LHV	kJ/kg	23395	21479
HHV	kJ/kg	24079	22661

Table 6.4 Results of the sensitivity analysis

Parameter	Unit	s1	s2	s3	s4
Gross electric power	MW	724,1	723,6	769,318	673,7
Gross electric efficiency	%	46,53	46,75	49,7	47,41
Net electric power	MW	535,79	541,08	588,918	504,72
Net electric efficiency	%	34,62	34,96	38,05	35,52
Fuel flow rate	kg/s	66,16	66,16	66,16	66,16
Fuel LHV	kJ/kg	23395	23395	23395	21478,6
Oxygen flow rate	kg/s	129,5	129,5	129,5	121,8
Pure oxygen flow rate	kg/s	125,1	125,1	125,1	117,7
ASU gross power consumption	MW	103,09	97,78	97,68	91,85
ASU specific gross power consumption per ton of pure oxygen	MJ/kg	0,8241	0,7816	0,7808	0,7807
ASU specific net power consumption per ton of pure oxygen	MJ/kg	0,689	0,675	0,660	0,666

The change of the ambient conditions (case s1) influences the temperature of cooling water which in turn increases the condenser pressure. The change of ambient conditions influences also the electric power consumed by air compressors.

Within the case s2, the cooling water temperature has been changed independently of ambient conditions, which may represent different design of the cooling system for the same power unit location. This change influences the condenser pressure and slightly air compressor powers through intercoolers.

Third sensitivity analysis (case s3) considers the change of steam cycle parameters - temperature and pressure of live steam and temperature of reheated steam. Assumed values of 700^{o}C represent future, today not commercial potential.

Last sensitivity analysis case (s4) considers the change of fuel parameters. The change of fuel caused changes in boiler island, especially in excess air and in increase in oxygen content in flue gas.

7 Conclusions

Several improvements have been proposed to the assumed 1st-gen oxy-fuel power unit. They are focused mostly on ASU integration with boiler and steam cycle.

Results of air-fired and 1st-gen oxy-fuel reference plants modelling indicate that the net efficiency drop because of oxy-fuel implementation is equal to 10,3 percentage points.

Heat recovery from the ASU compressors into steam cycle may be an effective way for improving the oxy-fuel system efficiency. Comparison of cases 1 and 1a leads however to conclusion, that independently of condensate preheating, the conventional, deeper cooling of compressed air by cooling water must be applied in order to reduce the compression work. Moreover, comparing cases 1a and 2a, an advantage of adiabatic compression with final cooler over intercooled compressor can be seen. There are two reasons for this tendency, first, the compressor efficiency is higher in the latter case, second the temperature of heat recovered to steam cycle is higher resulting in higher increase of power production. The final compressed air cooling by cooling water is also profitable in case 2a. Maximal increase of net efficiency due to ASU – steam cycle heat integration takes place in case 2a and is equal to 0,7 percentage point over the 1st-gen oxy-fuel system.

Results of cases 3 and 3a, which represent oxygen preheating indicate, as expected, the thermodynamic advantage of such integration. The use of flue gas instead of steam for oxygen preheating contributes to higher efficiency of the whole plant, but the capital cost for the gas-gas heater may be problematic. The net plant efficiency increase obtained in case 3a is equal to 1,1 percentage points over the 1st-gen oxy-fuel system.

The improvement based on increased oxygen content in oxidizer supplied to boiler (case 4) is not strictly related to ASU integration, but has been included as additional potential way for efficiency improvement. The increase of net plant efficiency is indeed visible and is related to the decreased flue gas flow rate in the boiler and lower temperature of the flue gas leaving the rotary heat exchanger. The net plant efficiency increase obtained in case 4 is equal to 1,1 percentage points over the 1st-gen oxy-fuel system.

All the improvements analyzed within cases 1-4 where treated as independent, single ideas. It is however, important to know, what is the change of efficiency and other parameters when the single ideas will be integrated within one system. Such an accumulation has been implemented in case 5 where ideas of most promising single cases (2a, 3a and 4) are incorporated. In conclusion, the net efficiency increase in case 5, over the 1st-gen oxy-fuel reference is equal to 2,6 percentage points which is however lower than a simple sum of efficiency increments (2,9) obtained within single 2a, 3a and 4 cases.

Thermal Integration of ASU with boiler and steam island increases the net oxy-fuel system efficiency. Another parameter, which clearly illustrates this tendency is ASU specific net power consumption per ton of pure oxygen, which has also been calculated for all analyzed cases. This parameter accounts not only for ASU electricity requirement, but also for electricity equivalent of steam consumption and for additional power credits due to additional electricity output generated by the steam cycle. The reduction of ASU specific net power consumption between 1st-gen oxy-fuel reference and case 5 plants is equal to 0,088 MJ per ton of pure oxygen produced.

Results of sensitivity analysis indicate, as expected, different oxy-fuel system efficiencies in different design ambient, fuel and live steam conditions. The deviations from the case 5 net efficiency are within the range of 0,22 – 2,3 percentage points. For the assumed values of changed parameters within cases s1 – s4, the only positive impact on efficiency is in the case of higher steam parameters, for which the net oxy-fuel system efficiency is equal to 38,1 %.

References

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