Open Access Journal

Journal of Power Technologies 93 (3) (2013) 133–141

`journal homepage:papers.itc.pw.edu.pl`

Analysis of the use of waste heat in an oxy-combustion power plant to replace steam cycle heat regeneration

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Abstract

Oxy-combustion technology is based on the burning of fuel in an oxygen-rich oxidant atmosphere. By eliminating nitrogen from the combustion process, the flue gas mainly consists of carbon dioxide and water vapor, allowing for the separation of CO_2 from flue gas at a relatively low energy cost. However, production of high purity oxygen entails significant electricity consumption. The object of analysis is a supercritical oxy-combustion coal-fired power plant. Auxiliary power demand is associated with the work of compressors in the cryogenic air separation unit and the installation of flue gas conditioning. This paper presents the results of thermodynamic analysis for different cases of compression installations organization extracted from individual blocks of the oxy-combustion unit. Analyzes were designed to identify potential for reducing energy consumption in the compression process by appropriate organization and to define the energy potential of using the heat recovered in cooling and condensation in the individual sub-processes to replace low-pressure regeneration.

Keywords: Thermodynamic analysis, Oxy-combustion, Gas compression, Replacement of regenerative heat exchangers

1. Introduction

The basic energy source to produce electricity in Poland is coal, with the share in 2010 reaching almost 87% [1]. Popularity of coal is the result of large deposits of this fuel in Poland, and consequently, good availability and low price in comparison to other fuels. Therefore, the development of clean coal technologies is an essential objective of Polish energy policy. Its implementation is possible through obtaining higher and higher efficiency of coal to electricity conversion while maintaining the increasingly stricter environmental protection standards [2, 3].

Anthropogenic CO_2 emissions affect the balance of natural carbon cycles. Actions are proposed to halt the upward trend in CO_2 concentration in the atmosphere [4].

In recent years the European Union has focused strongly on reducing emissions of greenhouse gases, in particular carbon dioxide. Since increases in the efficiency of electricity production are not sufficient to reduce CO_2 emissions to the desired level, it will be necessary to use the carbon capture and storage technology (CCS) to enable coal-fired electricity production to achieve almost zero CO_2 emissions.

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The driving force of the development and application of the carbon capture and storage technology is the European emissions trading system (ETS) [5]. The legal basis and principles of operation were defined in the Directive 2003/87/EC [6], replaced in 2009 by the Directive 2009/29/EC [7].

The aim of a CCS installation is separation of CO_2, followed by preparation for transport to the place of storage. There are three distinct types of CCS technologies:

- post-combustion,
- pre-combustion,
- oxy-fuel combustion.

Oxygen combustion concept is based on the combustion of fuel in an oxidant atmosphere with increased proportion of oxygen. Recirculation can be used to maintain an adequate share of oxygen for suitable combustion conditions, i.e. recycling part of the flue gas stream from behind the boiler to the combustion chamber. By eliminating nitrogen from the combustion process, the flue gas mainly consists of carbon dioxide and water vapor, allowing for relatively low energy cost separation of CO_2 from the part of the flue gas that is not recirculated. Subsequently, the separated carbon dioxide is prepared for transport and storage. The requirement here is to obtain thermodynamic parameters to provide transmission of CO_2 in a liquid form. Although the process of carbon dioxide separation in oxycombustion systems is connected with low energy consumption in relation to the post- and pre-combustion technology, still within the structure, a significant electricity demand for the oxygen separation should be factored in. At present, due to the requirement of high performance and a sufficient purity of oxygen, the use of a cryogenic air separation unit (ASU) in an oxy-combustion system is considered. The power demand of a cryogenic ASU is mainly dependent on the purity of the oxygen produced and is in the range 0.32–0.35 kWh/m_n^3 (for 95% purity). Oxy-combustion systems are about 7–11% less efficient than traditional systems [8].

2. Influence of gas separation on the efficiency of an oxy-combustion plant

The object of analysis is a supercritical oxy-combustion coal-fired power plant. A schematic of the unit is shown in Fig. 1. The steam cycle structure may be considered as a reference solution for supercritical power plants planned in Poland. For the plant the following were assumed:

- Reference gross electrical power $N_{el.REF}$ = 460 MW,
- Live steam parameters 29 MPa/600°C,
- Reheated steam parameters 4.8 MPa/600°C,
- Feedwater temperature 297°C.

The system consists of four basic technological blocks: the boiler, the steam cycle, the cryogenic ASU and the flue gas conditioning unit. For the analysis, three additional gas compression installations were extracted from the individual blocks, i.e. compression of air for the oxygen separation, compression of pre-cleaned flue gas for remaining moisture separation and compression of separated CO_2 in order to prepare for transport to a place of storage. The extracted installations are shown in Fig. 1.

The unit consists of a pulverized coal-fired boiler, designed for supercritical parameters (600°C, 30 bar), working with oxy-combustion technology. Bituminous coal was used as fuel, having the following composition: 8.76% ash, 22.37% moisture, 52.63% carbon, 3.43% sulfur, 7.5% nitrogen, 11.02% oxygen. The steam cycle consists of an extraction-condensing steam turbine, a condenser, a deaerator, four low-pressure regenerative heat exchangers, three high-pressure regenerative heat exchangers and a steam cooler. Oxygen to the boiler is provided by the cryogenic ASU, which is supplied by air at a pressure of 0.6 MPa. Oxidant obtained from the ASU consists of 95% O_2 and 5% N_2. An oxygen concentration of 30% is maintained in the boiler combustion chamber by exhaust gas recirculation.

For the purpose of the analysis a commercial GateCycle^{TM} program was used to model units consistent with the studied cases (Case A, B, C and D).

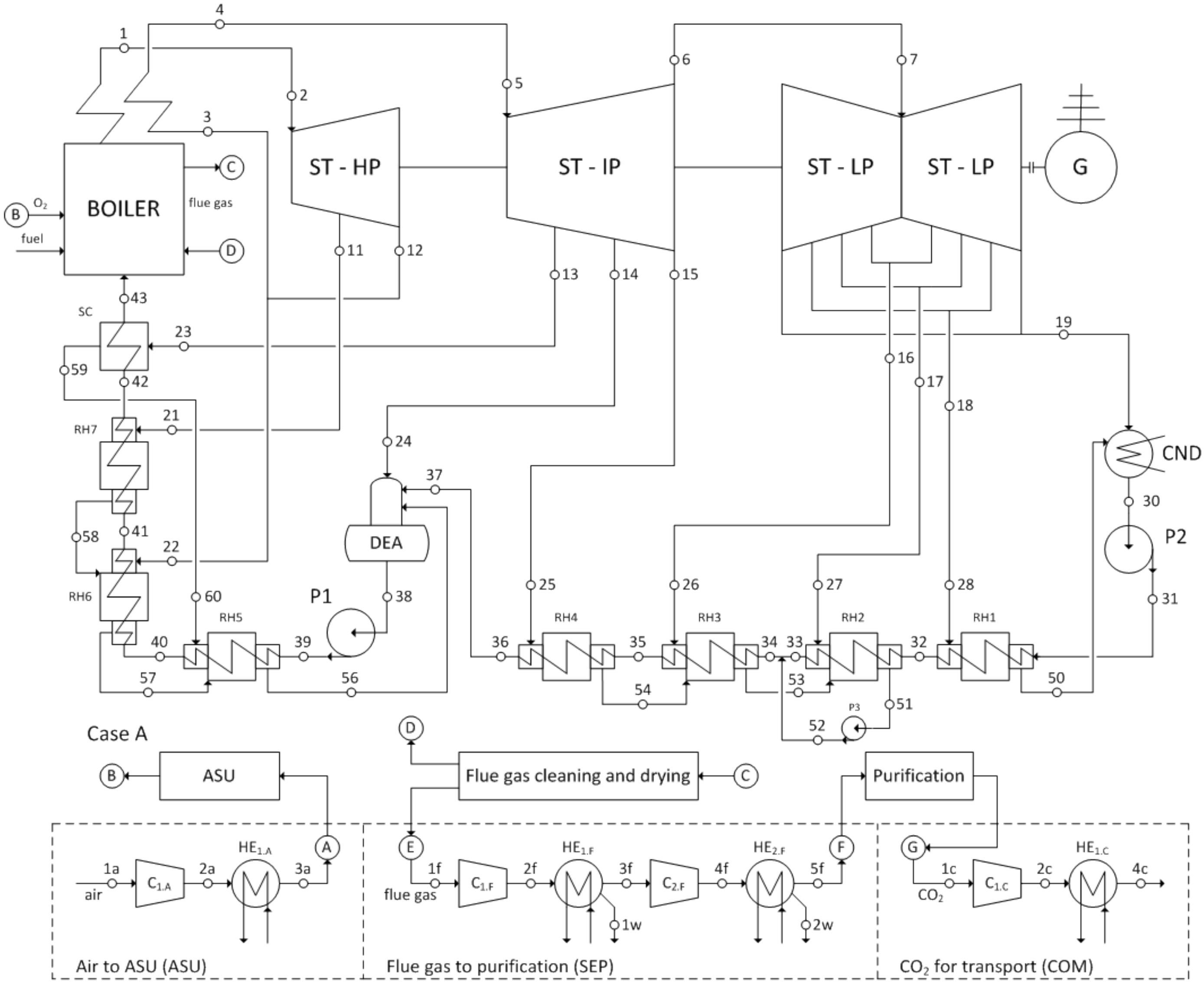

Figure 1: Diagram of the oxy-combustion coal-fired power plant with CO_2 capture

The GateCycle program is a PC based software application that performs detailed analyses of thermal power systems [9]. An Aspen Plus program was used for the calculations of the cryogenic ASU installation and the flue gas separation installation [10]. The models provided information about: (I) parameters at characteristic points of the gas compression installations and (II) important results regarding power demand of primary machines and devices. Also significant for the analysis was information about the composition of flue gas generated in the boiler and energy efficiency of this device ($\eta_K = 93.12\%$). Model of the boiler is described in detail in [11, 12].

Flue gas generated in the combustion chamber purified and adapted to the requirements of transport in four steps. First, exhaust gas leaving the boiler is dried to a certain degree and purified of dust and sulfur oxides in the flue gas cleaning and drying installation. The flue gas is then divided into (I) a stream that is recycled to the boiler and (II) a stream that is directed to the flue gas purification installation. In the first part of this installation the flue gas is deeply dehumidified. This process involves sequentional compression and cooling, which leads to moisture condensation. Drying reduces the risk of corrosion of gas pipelines and avoid icing in the separation process. The compressed and dried flue gas is directed to the CO_2 purification installation, in which non-condensing gases (such as argon, nitrogen, oxygen, sulfur dioxide) are separated in a cold-box with the use of phase separation phenomenon. The whole installation consists of multi-stream heat exchangers, phase separators and throttle valves. Finally, the obtained gaseous carbon dioxide with the required purity (>90%) is compressed to a pressure of 15 MPa to prepare for transport and storage. Energy consumption in the whole cleaning installation is the result of the compressors' work.

The paper presents the results of the thermodynamic analysis for different cases of compression installations organization extracted from individual blocks of the oxy-combustion unit. The case shown in Fig. 1 is the reference case, defined as Case A. Analyzes aimed to identify potential for reducing energy consumption in the compression process by appropriate organization and, optionally, to define the energy potential of using the heat recovered in cooling and condensation in the individual sub-processes to replace low-pressure regeneration.

3. The influence of the gas separation on the oxy-combustion unit efficiency

According to the diagram in Fig. 1 the influence of compression processes in extracted installations within the block on the electricity generation efficiency is identified by the relationship:

$$\eta_{el.net} = \eta_{\text{el.gross}} \cdot (1 - \delta_{\text{C}} - \delta^{*}) \tag{1}$$

where: δ^{*}—auxiliary power rate of the remaining installations in the unit, δ_C—auxiliary power rate of the compression installations, defined as the ratio of power demand of compressors ($\sum N_{el.C}$) to the gross electrical power of the plant ($N_{el.gross}$):

$$\delta_C = \frac{\sum N_{el.C}}{N_{el.gross}} \tag{2}$$

Energy consumption of the CCS installation in oxy-combustion technology in the analyzed unit results primarily from the need to power the compressors working in three technological blocks:

- Installation of cryogenic air separation unit (ASU),
- Installation of flue gas conditioning (SEP),
- Installation of carbon dioxide preparation for the transport (COM).

Therefore, the total power demand of the compressors in the oxy-combustion unit ($\sum N_{el.C}$) is the sum of the compressors' energy consumption in the mentioned blocks:

$$\sum N_{el.C} = N_{el.ASU} + N_{el.SEP} + N_{el.COM} \tag{3}$$

Parameters and compositions of the compressed gases in each compression section are presented in Table 1. The specific values listed in the table are the results of calculations performed using an oxy-combustion block model, or assumptions for the compression installation requirements. The symbols of characteristic points in the installation correspond to those used in Figure 1.

Table 1: Parameters of compressed gases

Parameter	Unit	ASU (1a)	SEP In (E)	SEP Out (F)	COM (G)
Mass flow $\dot{m}$	kg/s	361.64	102.62	98.21	92.24
Inlet pressure p_{in}	MPa	0.101325	0.101325		2.624
Inlet Temperature t_{in}	°C	15.00	46.07		30.00
Outlet pressure p_{out}	MPa	0.600	3.648		15.000
Pressure ratio β	–	5.92	36.00		5.72
Components:					
CO_2	–	–	0.7901	0.8745	0.9237
O_2	–	0.2100	0.0498	0.0551	0.0338
N_2	–	0.7820	0.0157	0.0174	0.0072
Ar	–	0.0080	0.0385	0.0426	0.0256
SO_2	–	–	0.0059	0.0065	0.0070
H_2O	–	–	0.1000	0.0039	0.0027

In Case A, as shown in Figure 1, for the ASU installation a single section compressor is used. In the installation of the flue gas conditioning a double section compressor with inter-section cooling and moisture removal works. A single section compressor is used in the preparation of CO_2 for transport. Compressed gases leaving each compression installation are cooled.

The use of multi-section compressors with intercooling is the reasonable practice for reducing the energy consumption of the compression process. Case B and Case C were created to assess energy requirements for the use of more extended separation installations.

In Case B compression of air to ASU is assumed in a double section compressor, and the compressor in flue gas conditioning is expanded to three sections. A structure with a liquid pump is introduced into CO_2 compression to prepare for transport. The gas is compressed in a single section compressor to a sub-critical pressure (6.5 MPa), then condensed by cooling. The assumed pressure of 15 MPa is achieved by a liquid CO_2 pump. In Case C the number of compressor sections is increased by one, related to Case B. Schemes of compression segments in Cases B and C are shown in Figure 2.

Division of compressors into sections is guided by the following basic principles:

- The same pressure ratio was applied in each section of the compressors used in the individual compression installations.

Table 2: Isentropic efficiency and outlet pressure of compressors sections

ASU	SEP	COM
	Case A	
$\eta_{C1.A} = 0.85$	$\eta_{C1.F} = 0.83$	$\eta_{C1.C} = 0.62$
$p_{2a} = 0.600$ MPa	$p_{2f} = 0.608$ MPa	$p_{2c} = 15.00$ MPa
	$\eta_{C2.F} = 0.77$	
	$p_{4f} = 3.648$ MPa	
	Case B	
$\eta_{C1.A} = 0.85$	$\eta_{C1.F} = 0.83$	$\eta_{C1.C} = 0.70$
$p_{2a} = 0.247$ MPa	$p_{2f} = 0.335$ MPa	$p_{2c} = 6.500$ MPa
$\eta_{C2.A} = 0.85$	$\eta_{C2.F} = 0.80$	$\eta_{PC} = 0.80$
$p_{4a} = 0.600$ MPa	$p_{4f} = 1.105$ MPa	$p_{6c} = 15.00$ MPa
	$\eta_{C3.F} = 0.77$	
	$p_{6f} = 3.648$ MPa	
	Case C	
$\eta_{C1.A} = 0.85$	$\eta_{C1.F} = 0.83$	$\eta_{C1.C} = 0.75$
$p_{2a} = 0.183$ MPa	$p_{2f} = 0.248$ MPa	$p_{2c} = 4.130$ MPa
$\eta_{C2.A} = 0.85$	$\eta_{C2.F} = 0.81$	$\eta_{C2.C} = 0.70$
$p_{4a} = 0.332$ MPa	$p_{4f} = 0.608$ MPa	$p_{4c} = 6.500$ MPa
$\eta_{C3.A} = 0.85$	$\eta_{C3.F} = 0.79$	$\eta_{PC} = 0.80$
$p_{6a} = 0.600$ MPa	$p_{6f} = 1.489$ MPa	$p_{6c} = 15.00$ MPa
	$\eta_{C4.F} = 0.77$	
	$p_{8f} = 3.648$ MPa	

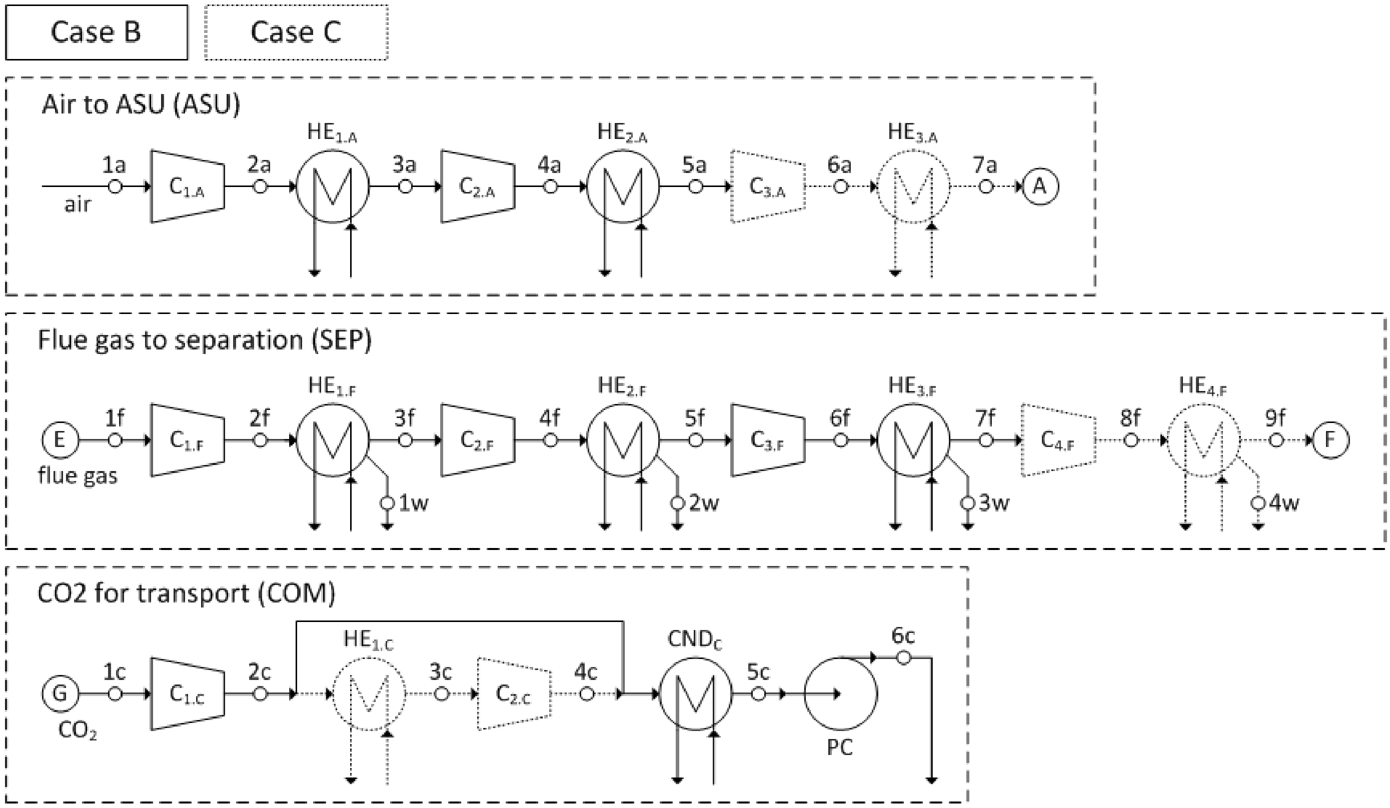

Figure 2: Diagram of the segments of gas compression units for Case B and Case C

- Gases after every compressor section are intercooled to gas temperature of 30°C.

The assumed outlet pressures and isentropic efficiency of each compressor section in Cases A, B and C are presented in Table 2. Electromechanical efficiency of all compressors is assumed at 98%. The results of a comparative analysis of Cases A, B and C are presented in Section 5.

4. Connection of CCS installation with the steam cycle

Energy consumption of the compression process contributes to a decrease in net efficiency of the oxy-combustion unit according to equations (1)–(3). Decreasing the average gas temperature in the compressor reduces the compression process work. The heat received by intercooler can be dispersed to the ambient, or if the temperature level is high enough it may be used in the unit's steam cycle. For example, use of this heat to replace heat regeneration in the steam cycle makes it possible to reduce steam bleedings and consequently results in increased steam turbine power. As noted in [13], this practice leads to higher electric efficiency and, at the same time, to lower energy efficiency of the steam cycle.

The reference system (Case A) is the basis for Case D, in which part of the compressed gases heat is used in a steam cycle according to the scheme in Figure 3. For the analysis it was assumed that all the parameters of the compressors remain the same as in the reference model.

In this case, to calculate equations (1) and (2), $N_{el.gross}$ should include growth in a steam turbine electric power ΔN_{ST}:

$$N_{el.gross} = N_{el.REF} + \Delta N_{ST} \tag{4}$$

The complete replacement of heat exchangers RH1–RH4 leads to the elimination of steam bleedings in the low-pressure section of steam turbine and to the elimination of steam collection from the fleeting between medium and low pressure steam turbine sections. In the calculations the same temperatures and pressures in other characteristic points of steam cycle as in the reference case were assumed.

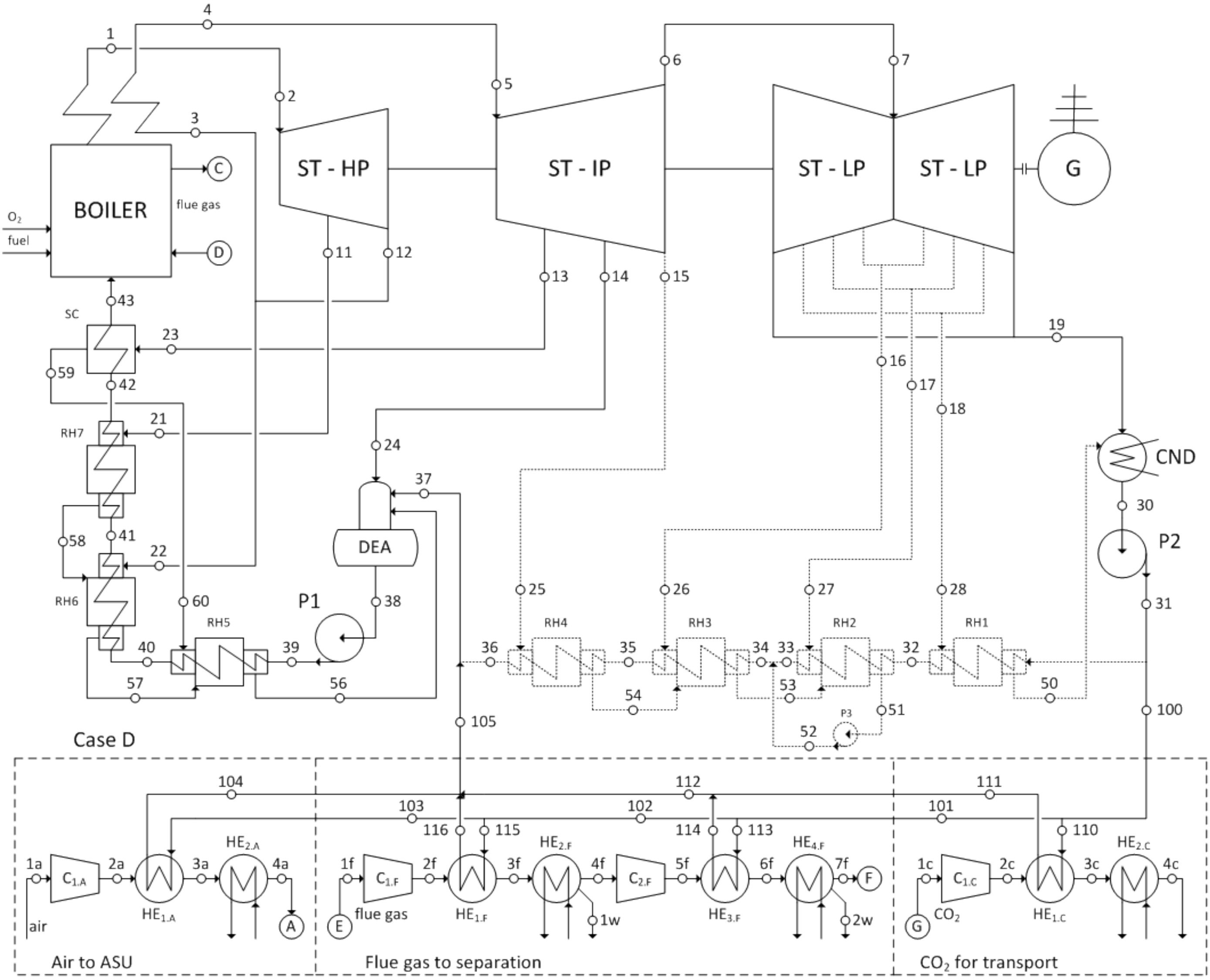

Figure 3: Scheme of integration of CCS installation with steam cycle in the oxy-fuel power plant

With the assumptions made and using the structure in Fig. 3, to replace all low pressure regenerative heat exchangers the heat flux need to be supplied in the amount :

$$\dot{Q}_{rec} = \dot{m}_{37} \left(h_{37} - h_{31} \right) \tag{5}$$

where: $\dot{m}$ and h—mass flow and water enthalpy, respectively, in points marked in Fig. 3.

In the reference system for the replacement of the whole low-pressure regeneration the needed thermal power amounts $\dot{Q}_{rec} = 124.40$ MW$_{th}$. According to Fig. 3 heat flux $\dot{Q}_{rec}$ is a part of the heat taken from the cooling of the gases in compression installations. The remaining heat from the gases cooling and condensation heat are dispersed in the ambient by additional coolers placed behind the primary heat exchangers. Use of this part of heat in the steam cycle is limited by its low temperature.

A preliminary analysis revealed that to heat the condensate to the required temperature of 150.18°C it is necessary to limit the number of compressor sections in the compression installation. That is why Case A is chosen as a base structure for Case D. In compressed gases coolers using condensate as a coolant, the temperature difference between factors at the cold end of exchanger assumed to be no less than 30 K.

5. Results

The basic results of analysis performed for all described cases are presented in Table 3.

The net electric power of the reference system is $N_{el.net} = 298.2$ MW, resulting in net efficiency at only $\eta_{el.net} = 30.46\%$. Auxiliary power rate of compression installations in this case is $\delta_C = 28.95\%$.

The analysis proved, that division of compressors into intercooled sections allows for significant reduction of the compressors electricity consumption. Total power demand of compression installations ($\sum N_{el.C}$) decrease related to the reference case is, respectively, 19.75 MW in Case B and 25.05 MW in Case C. The greatest percentage decrease in power demand was observed within CO_2 compression for transport ($N_{el.COM}$), as a result of liquid pump application.

Connection of the compression installations with the steam cycle in Case D allow the gross electric power of the steam turbine to increase by 20.6 MW, maintaining the power demand of compressors equal to Case A. This results in net efficiency increase to the value of $\eta_{el.net} = 32.57\%$, which is slightly better than achieved in Case B, but lower than Case C.

6. Discussion and conclusions

- Auxiliary power demand of the compression installations in oxy-combustion systems can be reduced by dividing the compressors into sections with gas intercooling, and by the use of the heat taken by gas coolers in the steam cycle. Division of compressors into sections brings expected results. In the analyzed cases B and C the auxiliary power ratio δ_C is reduced, respectively, by 4.30 and 5.45 percentage points, what gave an improvement of net electric efficiency by 2 to 2.6 percentage points. Increasing the number of compressor sections leads to a rise in efficiency, but this is subject to the law of diminishing returns.

- Connection of the compression installation with the steam cycle leads to an increase in steam turbine electric power, giving a rise in net electric efficiency of 2.1 percentage points, relative to the reference case.

- It should be underlined that the potential for the use of waste heat within CCS installation in the steam cycle is dependent on the installation used and the operating parameters of the units. That is why integration of the CCS installation with the steam cycle should be done on a case-by-case basis for each power plant and optimized through the analysis of multiple variables to find the maximum net electric efficiency $\eta_{el.net}$.

- The final evaluation measure should be the economic efficiency of the various solutions considered. For optimization aimed at improving economic performance indicators it is necessary to determine investment cost, which can vary greatly for individual cases. For this reason the results of the economic assessment should form the basis for investment recommendations.

Table 3: Selected characteristic parameters of the considered cases

Parameter	Unit	Case A	Case B	Case C	Case D
Gross electrical power $N_{el.gross}$	MW_{el}	460.000			480.600
Heat flux to the steam cycle $\dot{Q}_{in}$	MW_{th}	911.502			
Boiler energy efficiency η_K	–	0.9312			
Chemical energy of fuel $\dot{P} \cdot LHV$	MW_{th}	978.847			
Gross electrical efficiency $\eta_{el.gross}$	–	0.4699			0.4910
Power demand of ASU installation $N_{el.ASU}$	MW_{el}	83.269	74.612	71.979	83.269
Power demand of SEP installation $N_{el.SEP}$	MW_{el}	34.075	30.832	29.288	34.075
Power demand of COM installation $N_{el.COM}$	MW_{el}	15.803	7.956	6.826	15.803
Total power demand of compressors $\sum N_{el.C}$	MW_{el}	133.147	113.400	108.093	133.147
Auxiliary power rate of the remaining installations in the unit δ^*	MW_{el}	0.0623			0.0596
Auxiliary power rate of the compression installations δ_C	–	0.2895	0.2465	0.2350	0.2770
Net electrical power $N_{el.net}$	MW_{el}	298.205	317.952	323.260	318.803
Net electrical efficiency $\eta_{el.net}$	–	0.3046	0.3248	0.3302	0.3257

- The next stage of analysis will be creation of a compression installation structure using the advantages of all the cases discussed here, and optimization of the created structure.

Acknowledgments

The results presented in this article were obtained from research work co-financed by the National Center for Research and Development within the framework of Contract SP/E/2/66420/10—Strategic Research Programme—Advanced Technologies for Energy Generation: Development of a technology for oxy-combustion pulverized-fuel and fluid boilers integrated with CO_2 capture.

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