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The influence of selected parameters on the efficiency and economic charactersistics of the oxy-type coal unit with a membrane-cryogenic oxygen separator

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Abstract In this paper a 600 MW oxy-type coal unit with a pulverized bed boiler and a membrane-cryogenic oxygen separator and carbon capture installation was analyzed. A membrane-cryogenic oxygen separation installation consists of a membrane module and two cryogenic distillation columns. In this system oxygen is produced with the purity equal to 95%. Installation of carbon capture was based on the physical separation method and allows to reduce the CO_2 emission by 90%. In this work the influence of the main parameter of the membrane process – the selectivity coefficient, on the efficiency of the coal unit was presented. The economic analysis with the use of the break-even point method was carried out. The economic calculations were realized in view of the break-even price of electricity depending on a coal unit availability.

Keywords: Oxygen production; Membrane air separation

Nomenclature

A	–	depreciation
A_M	–	membrane area, m^2
BEP	–	break-even price of electricity, €/MWh
C_{op}	–	operating costs
C_{wc}	–	change of the working capital

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CF_t	–	cash flow
E_{MEM}	–	energy intensity of the membrane installation, kWh/kgO_2
$E_{MEM-CRYO}$	–	energy intensity of the membrane-cryogenic installation, kWh/kgO2
F	–	cost of financing
J	–	investment costs
k_M	–	unit cost of membrane module, €/m^2
K_M	–	cost of membrane module, €
K_{VENT}	–	unit cost of fan
K_{VP}	–	cost of vacuum pump
L	–	salvage value
m	–	mass flow, kg/s
m_p	–	coal stream directed to the coal unit, kg/s
M_{O2}	–	oxygen molar mass, kg/kmol
N	–	last year of duration of a project
N_{el}	–	electric power produced in the power plant, kW
N_{el_ASU}	–	electric power required to drive of ASU devices, kW
N_{el_BD}	–	electric power required to drive of boiler devices, kW
N_{el_CCS}	–	electric power needed to drive of CCS devices, kW
$(N_{el})_{COMP}$	–	electric power of compressor used in cryogenic module, kW
N_{el_SC}	–	electric power required to drive of steam cycle devices, kW
$(N_{el})_{VENT}$	–	electric power of fan, kW
$(N_{el})_{VP}$	–	electric power of vacuum pump, kW
NPV	–	net present value
n_{O2}	–	oxygen molar stream, kmol/h
n_P	–	permeate molar stream, kmol/h
P	–	permeability coefficient
p_{atm}	–	atmospheric pressure, Pa
p_F	–	partial pressure on the feed side
p_P	–	partial pressure on the permeate side
p_{perm}	–	pressure on the permeate side, Pa
r	–	discount rate
S	–	revenues from sale
T_{in}	–	income tax
t	–	consecutive year of consideration from the beginning of the construction system
LHV	–	lower heating value of coal, kJ/kg
x	–	membrane thickness
X	–	component concentration in the feed stream
Y	–	component concentration on the permeate side
(Y_{O2})	–	oxygen concentration of permeate
$(Y_{O2})_{CRYO}$	–	oxygen concentration in final product from cryogenic distillation column

Greek symbols

β	–	pressure ratio
η_i	–	isentropic efficiency

Subscripts

$VENT$	–	fan
VP	–	vacuum pump

1 Introduction

In Poland 95% of electricity is generated with the use of coal (61% hard coal, 34% lignite) [1]. Main advantages of the use of coal is its availability (and uniformity of distribution of resources) and price stability. As a result energy technologies based on coal will play a dominant role in the power industry today and in the future. The primary objective of the European Union energy policy is the reduction of carbon dioxide (CO_2) anthropogenic emissions into the atmosphere by 20%, because the greenhouse gases have a negative impact on climatic changes in the earth's atmosphere [2].

The reduction of CO_2 emissions can be achieved, among others, by increasing the efficiency of electricity generation and the use of CO_2 sequestration systems. A significant increase of efficiency of fossil fuels conversion can be achieved though the use of supercritical steam parameters – power plant efficiency for such a solution increases to approx. 50% [3].

The following methods of CO_2 separation can be considered: carbon capture after combustion process, capture before combustion and combustion in the atmosphere of oxygen and recirculated flue gases. The CO_2 capture technology before combustion uses the process of fossil fuels gasification, while in CO_2 separation technology after combustion, CO_2 is removed from the produced flue gas stream. In both methods, however, the power plant efficiency is significantly reduced [4–6].

Less energy intensive solution is oxy-combustion method [7], where the exclusion of nitrogen from the oxidant fed to the combustion chamber causes the increase of the CO_2 concentration in the generated flue gases, which results in the subsequent possibility of uncomplicated sequestration of CO_2. The advantage of oxy-combustion technology is the fact that this method can be used to retrofiting units currently operated by construction of the air separation plant, an installation for further CO_2 purification and the exhaust gas recirculation system to the boiler structure.

2 Scheme of the 600 MW coal unit

The analyzed coal unit with a gross capacity of 600 MW includes: pulverized bed boiler with live steam parameters of 650 °C/31.1 MPa and reheated steam parameters of 670 °C/6.15 MPa, steam cycle, membrane – cryogenic oxygen separation plant, carbon capture installation. Integrated with coal unit membrane-cryogenic oxygen separator consists of membrane module and two cryogenic distillation columns. In this installation the membranes made of polymer material were used, whereby the oxygen concentration in the air is increased to the level of 40%, and separated stream is directed to the cryogenic module. In the cryogenic air separator the product is obtained with a final purity of 95%. Oxygen plant is integrated with the pulverized bed boiler, where resulting flue gases contain about 79% of CO_2, and in next step are directed to the drying and purification installation. The CO_2 sequestration system (carbon capture and storage – CCS) consists of: drying section, where excess water is removed, cryogenic distillation module, where the redundant nitrogen and oxygen are removed and compression section, where flue gases are compressed to the pressure of 15 MPa. The parameters of hard coal used in the coal unit read: carbon = 0.6125, sulfur = 0.011, hydrogen = 0.039, nitrogen = 0.0093, oxygen = 0.065, moisture = 0.1732, ash = 0.09 and the lower heating value is 24048 kJ/kg. Scheme of coal unit is shown in Fig. 1.
The net efficiency of the coal unit was calculated according to the following formula:

$$\eta_{el,N} = \frac{N_{el} - N_{el\_ASU} - N_{el\_BD} - N_{el\_SC} - N_{el\_CCS}}{m_p \, LHV} , \qquad (1)$$

where energy capacity of individual units of the power plant read: N_{el_BD} = 12.62 MW, N_{el_SC} = 19.6 MW, N_{el_CCS} = 45.23 MW. The net efficiency of the power plant with membrane-cryogenic oxygen separator is at the level of 36.47%.

3 Analysis of the membrane module

Membrane is a phase barrier, which can be used for selective separation of components. Membrane technology is used in many industries such as chemical, pharmaceutical, electronics, food, water purification and wastewater treatment, etc. The membranes are produced from different materials, i.e. can be of organic, inorganic and composite origin. Membranes for air

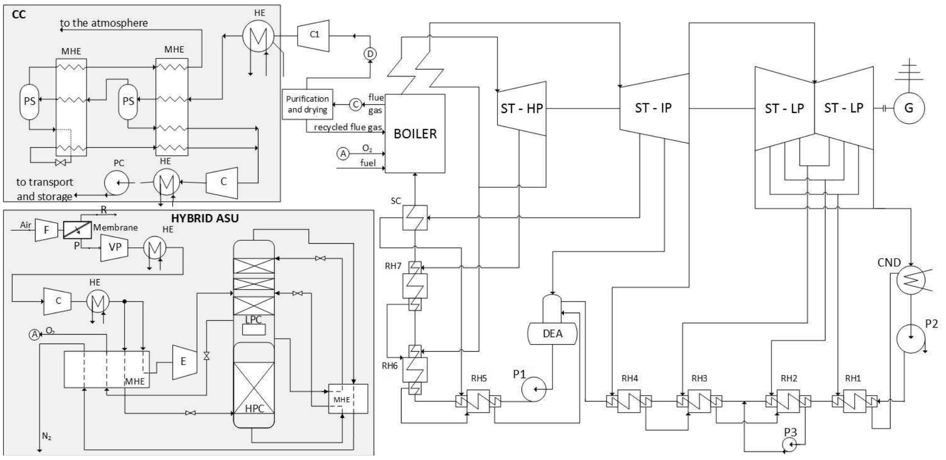

Figure 1: Scheme of the coal unit integrated with membrane-cryogenic oxygen separator: CC – carbon capture, MHE – multistream heat exchanger, PC – liquid CO_2 pump, C – compressor, PS — phase separation, HE – heat exchaner, RH – regenerative heat exchanger, CND – condenser, P1,P2,P3 – pump, ST – steam turbine, HP,IP,LP – high/intermediate/low-pressure, SC – steam cooler, G – generator, HPC – high pressure column, LPC - low pressure column, E – expander, F – fan, P – permeate, R – retentate.

separation are produced from a polymeric material such as ethyl cellulose, polyphenylene or polysulfone.

On the efficiency of the membrane process two main parameters have an influence: permeability and selectivity of the used membrane. Permeability is defined as the selected component stream permeated through the membrane. The selectivity coefficient, α, is the ratio of the permeabilities of the individual components, and in the case of the air the selectivity is a ratio of oxygen to nitrogen permeability:

$$\alpha = \frac{P_{O_2}}{P_{N_2}} . \tag{2}$$

Selectivity is a membrane material property. For the membranes made of polymer material the oxygen and nitrogen selectivity is a diminishing function with the increase of the O_2 permeability coefficient [9]. In present studies the a polymer membrane module with the following parameters is used: O_2 permeation coefficient $P_{O_2} = 0.31119$ $\mathrm{m}_N^3/\mathrm{m}^2\,\mathrm{h\,MPa}$, and N_2 permeation coefficient $P_{N_2} = 0.02922$ $\mathrm{m}_N^3/\mathrm{m}^2\,\mathrm{h\,MPa}$, [9], $\alpha = 10.6$.

In the membrane module the driving force for the process is produced by a fan on the side of the feed and the vacuum pump installed on the permeate side. For the energy reasons the lowest energy consumption for the membrane-cryogenic was determined. The demand for electricity needed to power the devices used is dependent on the feed and permeate streams. In the membrane model in order to determine the minimum of the energy intensity, constant parameters of the obtained stream and permeate purity were assumed, while as variables pressure of permeate and membrane surface area were treated.

For oxygen concentration of 22–50% of stream directed to the cryogenic module the membrane area and permeate pressure were calculated for the lowest energy intensity. Calculations were performed for the membrane with different coefficients of oxygen permeability and a different degree of selectivity. In Tab. 1 are summarized the assumptions of oxygen permeability coefficient, permeate pressure and oxygen concentration in permeate and the results of obtained minimal energy intensity for each membrane. The energy intensity in kWh/kgO_2 is determined from equation:

$$E_{MEM} = \frac{(N_{el})_{VENT} + (N_{el})_{VP}}{n_p\,(Y_{O2})\,M_{O2}}\ , \tag{3}$$

and electric intensity of membrane-cryogenic unit as

$$E_{MEM-CRYO} = E_{MEM} + \frac{(N_{el})_{COMP}}{n_{O2}\,(Y_{O2})_{CRYO}\,M_{O2}}\ . \tag{4}$$

Table 1: Main parameters of the membrane module.

Selectivity O_2/N_2	Oxygen permeability coefficient, $m_N^3/(m^2h\,MPa)$	Pressure on the permeate side, MPa	Oxygen concentration in the permeate	Energy intensity of the membrane module E_{MEM}, kWh/kgO_2	Energy intensity of the membrane--cryogenic installation $E_{MEM-CRYO}$, kWh/kgO_2
10.6	0.31119	0.039	41%	0.085	0.204
15	0.43837	0.03	50%	0.090	0.196
20	0.5844	0.032	50%	0.085	0.190
30	0.8766	0.034	50%	0.080	0.185

For the membrane characterized by a selectivity of 15–30 the lowest energy intensity can be achieved for the concentration of oxygen in the permeate at the level of 50%, because of the smaller permeate stream directed to the cryogenic unit, which results in a lower energy demand of compressors used in the cryogenic system. The influence of the selectivity coefficient on the net efficiency of coal unit was analyzed.

The net efficiency of coal unit was calculated according to the following relationship:

$$\eta_{el,N} = \frac{N_{\rm el} - [(E_{MEM} n_P (Y_{O2}) M_{O2}) + (N_{el})_{COMP})] - N_{el\_BD} - N_{el\_SC} - N_{el\_CCS}}{m_{\rm p} \, LHV} \tag{5}$$

The results are illustrated in Fig. 2. The net efficiency of coal unit for the membrane with selectivity coefficient of $\alpha = 10.6$ is 36.47% and it is increasing function with the increase of selectivity and is for $\alpha = 30$ equal to 37.02%. The calculation of energy intensity depending on selectivity coefficient can be found in [10].

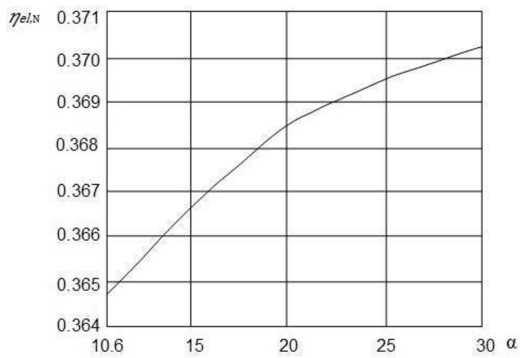

Figure 2: The dependence of the efficiency of the coal unit on the selectivity coefficient.

4 Economic analysis of the 600 MW coal unit integrated with membrane-cryogenic oxygen separator

The economic analysis was performed in order to assess the profitability of constructing of 600 MW coal unit with oxy-type pulverized bed boiler, hybrid membrane-cryogenic oxygen production installation and carbon capture system. One of the primary indicator of economic efficiency evaluation is the net present value method [8] where the net present value is defined as:

$$NPV = \sum_{\mathrm{t}=0}^{\mathrm{t}=\mathrm{N}} \frac{CF_{\mathrm{t}}}{(1+r)^{\mathrm{t}}} \,, \tag{6}$$

where cash flow, CF_t, is determined as follows

$$CF_{\mathrm{t}} = \left[S - J - (C_{OP} + T_{\mathrm{in}} + C_{\mathrm{wc}}) + A + F + L\right]_{\mathrm{t}} \,. \tag{7}$$

The economic analysis for each of the considered cases based on the break even point method was realized, to determine the break-even point (*BEP*) of the project which is the case in which the income from the sale of products equal to the cash outlays. In the break even point method the limit value of one of the components of the net cash flow, CF_t, is determined. The selected value is calculated for the condition $NPV = 0$. For the analysis the break-even price of electricity was assumed.

The economic analysis was performed for three variants of the power plant with power gross equal to 600 MW for every coal unit:

- the reference unit with the air-fired pulverized bed boiler without CO_2 separation installation, the net efficiency of this unit is at level of 45.82%;
- coal unit with oxy-type pulverized bed boiler integrated with cryogenic oxygen production installation and CCS system, the net efficiency of this unit is equal to 35.71%;
- coal unit with oxy-type pulverized bed boiler integrated with membrane-cryogenic oxygen separator and CCS system, the net efficiency of this unit is equal to 36.47% (as shown in Fig. 2 for $\alpha = 10.6$).

In Tab. 2 the main assumptions for the economic analysis are summarized.

On the basis of the assumptions the break-even price of electricity for each of the case was calculated and is equal to:

- for the reference unit: 62.9 €/MWh
- coal unit with cryogenic oxygen plant: 69.0 €/MWh
- coal unit with membrane-cryogenic oxygen plant: 70.8 €/MWh

Table 2: The main assumption for the economic analysis.

Specification	Unit	Value
Annual working time	h/a	7500
Reference unit investment costs	€/kW$_{gross}$	1400 [11]
Investment costs on the unit with cryogenic ASU	€/kW$_{gross}$	1850
Investment costs on the unit with membrane-cryogenic installation	€/kW$_{gross}$	2000
Construction time	years	3
Share of own financial resiurces	%	20
Share of commercial credit	%	80
Actual interest of commercial credit	%	6
Payback time of commercial credit	years	10
Operation time	years	20
Discount rate	%	6.2
Costs of operation	€/MWh	5.8
Costs of operation of CCS	€/MgCO_2	4.6
Coal price	€/GJ €/Mg	2.29 55
CO_2 emission certificate price	€/Mg	21.8
Employment in the reference unit	pers./MW	0.4
Employment in the unit with cryogenic and hybrid air separator	pers./MW	0.5
Monthly salary including related costs	€/post/month	1163
Average depreciation rate	%	6.67
Income tax rate	%	19
CO_2 emission incriminating of reference unit	kg CO_2/MWh	683
CO_2 emission incriminating a unit of coal unit with membrane – cryogenic separator	kg CO_2/MWh	20

The break-even price of electricity is the highest for the power plant with membrane – cryogenic air separator, what is caused by the high investment cost of hybrid oxygen installation.

The sensitivity analysis was made because of variable annual working time of coal unit on the break-even price electricity. Results are illustrated in Fig. 3. The change of annual operation time from the value of 7500 h to 8500 h caused the decrease of break-even electricity price of the every analyzed unit configuration, and of break-even price of electricity, C_{el_gr}, of every analyzed unit configuration, i.e., to 60.2 €/MWh for the reference unit, 64.4 €/MWh for the unit with cryogenic air separator, and

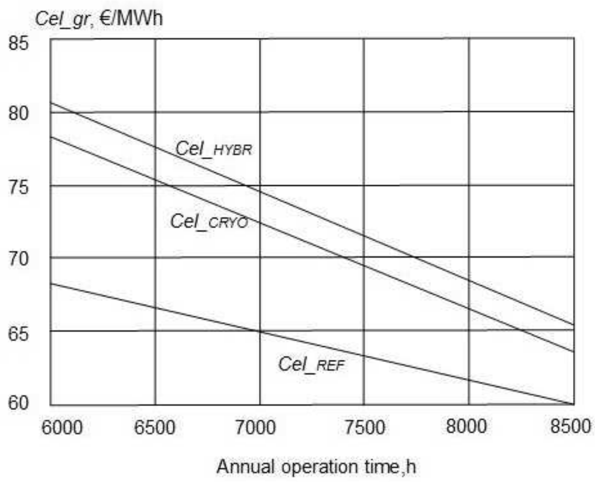

Figure 3: Break-even price of electricity, C_{el_gr}, as a function of annual operation time: C_{el_HYBR} – break-even price of electricity for the hybrid unit, C_{el_CRYO} – break-even price of electricity for the cryogenic unit.

65.9 €/MWh for the power plant with hybrid separator.

For the unit integrated with a membrane-cryogenic oxygen separator the cost of particular devices of membrane installation was calculated from the following relationships:

$$K_M = k_M\, A_M + 250000 \left(\frac{A_M}{2000}\right)^{0.7} , \tag{8}$$

$$K_{VENT} = 1.051 \frac{39.5\, m}{0.90 - \eta_{i,VENT}} \beta_{VENT} \ln \beta_{VENT} , \tag{9}$$

$$K_{VP} = 4\, 1.051 \frac{39.5\, m}{0.90 - \eta_{i,VP}} \beta_{VP} \ln \beta_{VP} , \tag{10}$$

with $\beta_{VENT} = 1.06$, $\beta_{VP} = \frac{p_{atm}}{p_{perm}}$. The costs of the membrane module for membranes with different selectivity coefficients were determined. The results are summarized in Tab. 3.

The membrane area was calculated using data from Tab. 1 using commercial software Aspen, which uses the equation for the permeate stream

$$dJ_i = \frac{P_i}{x}(p_F X_i - p_P Y_i) dA_m , \tag{11}$$

where subscript i denotes the i-component.

Table 3: Costs of the membrane module.

Selectivity	Membrane area, mln m^2	Price of membrane module, €/kW
10.6	2.058	222
15	1.334	158
20	1.349	158
30	1.364	158

The main component in the investment cost of the membrane module is the membrane itself, therefore investment costs are higher for air separation systems which require membrane with a larger surface area. For the analyzed cases, the highest investment cost must be incurred for the membrane with a selectivity coefficent of 10.6.

The calculations of break-even price of electricity for coal units with membranes with different selectivity coefficient were performed. The results are shown in Fig. 4. With the increase of O_2/N_2 selectivity of the membrane the price of electricity is reduced and is equal to 69.6 €/MWh for $\alpha = 30$.

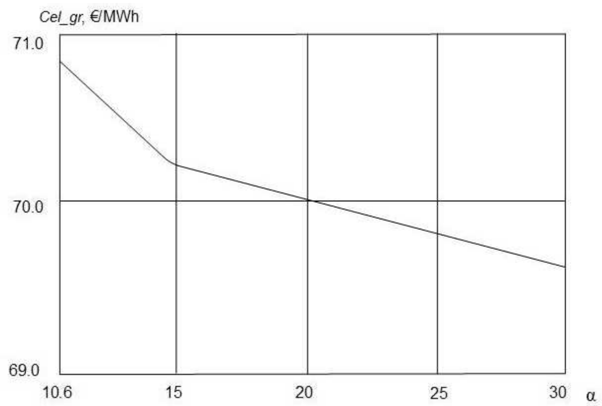

Figure 4: Break-even price of electricity as a function of membrane selectivity.

5 Summary

In this paper results of thermodynamic and economic analysis of coal unit with oxy-type boiler integrated with membrane-cryogenic oxygen plant and carbon capture installation are presented.The influence of selectivity of the membrane on the efficiency of the coal unit was tested.

The analysis showed that the increase of membrane O_2/N_2 selectivity increases the efficiency of the power unit. Sensitivity analysis of the break-even price of electricity depending on the availability of the power plant for three systems: reference, with cryogenic oxygen plant and membrane-cryogenic air separator was performed. If the coal unit availability increases from 7500 h/a to 8500 h/a, then the break-even electricity price will decrease as following: about 2.7 € for the reference unit, about 4.6 € for the power plant with cryogenic air separator, and about 4.9 € for the coal unit with hybrid oxygen separator. Economic analysis was also performed for power units with membranes of differing selectivity coefficient. The break-even price of electricity decreases with increasing degree of selectivity of the membrane and is minimal for the coal unit with the hybrid oxygen plant with membrane characterized by the selectivity factor of 30 and is equal to 69.6 €/MWh.

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