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The influence of membrane-cryogenic technology of oxygen separation from air on the efficiency of supercritical coal units with the CCS installation

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ABSTRACT

In this paper, a 600-MW power plant with the oxy-type coal-fired pulverized bed boiler, integrated with a membrane-cryogenic oxygen separator and carbon capture and storage installation, was analyzed. The proposed air separation plant can reduce the energy requirement for the oxygen production in comparison with the cryogenic technology, what influences the net efficiency of electricity production of the power plant. The hybrid, membrane-cryogenic oxygen separator consists of a membrane module and a double cryogenic distillation column, and enables to obtain oxygen of a purity of 95%. The auxiliary power of such a hybrid oxygen production installation was calculated. Several methods of energy consumption reduction were presented, that is, by using two section vacuum pump, by reducing the cooling temperature between sections of this machine to 20°C, by assuming lower flow resistance in the membrane module and by using membranes with improved separation properties towards oxygen and nitrogen. The auxiliary power rate of each technological installation of the power plant was calculated. The net efficiency of the oxy-type coal unit as a function of the selectivity parameter of the membrane was determined. Different options for improving the net efficiency of the coal unit were analyzed. In this paper, the economic analysis was also performed. The break-even price of electricity for the coal unit with oxygen membrane separator of different selectivity coefficients was calculated. The potential of electricity price reduction as a function of operating conditions in the membrane module of the hybrid separator was also presented.

Keywords: Membrane-cryogenic air separation unit; Oxy-type coal unit; Thermodynamic analysis; Economic analysis

1. Introduction

The increasing power demand is the determinant of incessant civilization development. Coal fuel plays the dominant role in power generation (according to International Energy Agency around 40% of electricity is globally produced from coal). The process of coal firing proceeds with the release of unfavorable chemical substances such as CO_2, SO_2 and NO_x, among which carbon dioxide has the largest influence on greenhouse effect. The world science concentrates on searching for clean energy technologies, which will make the production of electricity with very low emission of greenhouse gases possible. The use of carbon capture and storage (CCS) technology allows for a considerable reduction of CO_2 emission from coal (and gas) fired power plants. At present, the most widely used is post-combustion technology, in which CO_2 is captured from flue gases leaving air-fired boiler [1,2]. The main disadvantage of the carbon dioxide capture installations is their high energy requirements which, in consequence, lowers the overall net efficiency of a coal unit [2–4]. The methods based on oxy-combustion technology results in a smaller decrease of efficiency as compared with other CCS configurations [5–8]. Oxygen required for oxy-type boilers is typically produced in cryogenic air separators, which are characterized by the energy consumption of about 0.22–0.34 kWh $kg^{-1}O_2$ [9]. As a consequence of the large

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energy demand of oxygen generation and carbon capture and compression, the efficiency of a power plant drops by ca. 12-14 percentage points in comparison with the reference power plant (with a conventional boiler, in which the air is used as an oxidant) [10]. Thus, methods of oxygen production with lower energy demand and other ways of reduction of loss of efficiency are searched for. In this paper, the membrane-cryogenic oxygen production installation for a 600-MW oxy type coal unit was proposed to achieve this goal.

2. Separation of oxygen with the use of polymer membrane

Membrane installations for separation of nitrogen and oxygen from air are used from the 1980s of 20th century. Membrane module allows obtaining oxygen of purity ranging from 23% to 45%, with productivity of 5–5,000 m^3_N h^{-1} [11]. However, oxygen with such a purity cannot be used in an oxy type power unit, which usually requires purity above 95%.

The separation process depends on properties of the membrane material [12]. In this technology, the solubility-diffusion mechanism, which assumes, that the components penetrating through the membrane dissolve and diffuse along the pressure gradient, is used. The feed stream is separated on permeate and retentate streams. Permeate is a part of gas enriched in particles of component separated on the membrane, while retentate is the stream that is left before the membrane. The ability of separation of a given substance on a membrane is defined by permeability coefficient P_i, which is the unique property of membrane material. The ratio of permeability of two different components is called selectivity coefficient α. The principle of membrane gas separation is presented in Fig. 1.

The resulting product stream composition depends on membrane permeability, P_i, its thickness x, surface, A and the partial pressure difference of components on both sides of the membrane. It can be determined from Eq. (1):

$$dJ_i = \frac{P_i}{x}(p_F X_i - p_P Y_i)dA \tag{1}$$

3. Separation of oxygen with the use of cryogenic installation

In cryogenic installations, oxygen of the purity higher than 99%, can be produced on industrial scale, at the installation capacity of 4,000 tons per day [10,13]. The model of the air separation unit (ASU) was built using the Aspen Plus software. It was assumed that dried and purified air stream of the composition 0.209 O_2, 0.782 N_2 and 0.009 Ar is directed to the membrane part of the installation. The air temperature was assumed at 20°C, while the pressure at 1.013 bar.

The calculations were performed in order to obtain 100 kg s^{-1} of product stream at the purity of 95% O_2. The air at the inlet to the installation was compressed to 6.1 bar in a four-section compressor with interstage cooling to 30°C. The isentropic efficiency of the compressor was assumed at 0.9 and the mechanical efficiency at 0.98. The pressure ratio was

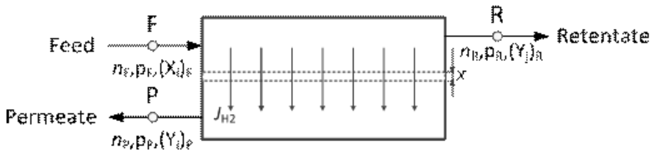

Fig. 1. The crossflow gas separation (*F* – feed, *P* – permeate, *R* – retentate).

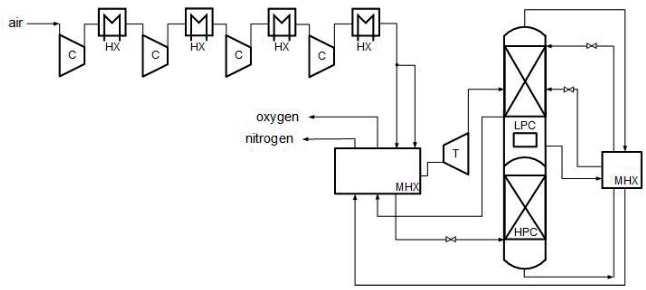

Fig. 2. The scheme of a double air separation column (HX – heat exchanger, MHX – multistream heat exchanger, C – compressor, T – turbine).

equal to 1.56. The feed stream was directed to a multi-stream heat exchanger, where it was cooled by the final products of separation and next it expanded in the valve to 5.9 bar. Then, the stream of air was directed to the high-pressure distillation column (HPC), which was operated at the pressure profile of 5.7–5.9 bar. The purity of oxygen after the HPC was 38%. Nitrogen and oxygen streams after HPC were directed to a heat exchanger, where they were cooled and then, after expansion, directed to the low-pressure column, where the pressure was assumed at 1.3–2 bar. The final product with the composition of 95% O_2 and 5% N_2 was obtained at the bottom of the LPC column, while at the top of the column nitrogen with the purity of 100% was produced. The schematic diagram of a cryogenic ASU is presented in Fig. 2.

The specific energy consumption of the cryogenic installation e_{CRYO} was calculated with the use of Eq. (2):

$$e_{CRYO} = \frac{\sum_i N_{el,C} - N_{el,T}}{n_{O_2} \cdot (Y_{O_2}) \cdot M_{O_2}} \tag{2}$$

The energy intensity of the cryogenic installation was determined on the basis of the modeling results and was equal to 0.222 kWh $kg^{-1}O_2$. It was a reference value for further calculations made for a hybrid ASU.

4. Hybrid membrane-cryogenic oxygen plant

In this study, a hybrid membrane-cryogenic air separation plant was proposed to produce oxygen for oxy-fuel power plant purposes. The main advantage of such solution is the possibility of reduction of energy requirement for oxygen production. A hybrid installation was composed of a membrane module, in which polymeric membranes [14,15] and cryogenic double distillation column were applied [14–16].

In the cryogenic technology, compression of air supplied to the columns requires high amount of electricity. In the hybrid installation, a stream with higher oxygen concentration (after membrane module) is directed to the cryogenic column. It causes a reduction of the energy consumption (due to a lower stream) of compressors in the cryogenic installation and, consequently, of the whole oxygen plant.

A membrane made of phenolic resin was chosen [17] for the analysis. The initial assumptions for the calculations of the hybrid installation were as follows:

- permeation coefficient of O_2: 3.1119 m^3_N $(m^2 \cdot h \cdot bar)^{-1}$,
- permeation coefficient of N_2: 0.2922 m^3_N $(m^2 \cdot h \cdot bar)^{-1}$,
- selectivity coefficient: 10.65,
- air temperature at the inlet to the membrane module: 15°C,
- air stream at the inlet to the membrane module: 100 kmol h^{-1},
- purity of the final product: 0.95 O_2, 0.05 N_2.

Air was supplied to the membrane module with the use of a fan, in which the pressure was increased by 0.05 bar. Negative pressure of the permeate was created by a vacuum pump. The oxygen-enriched permeate, after the membrane module, was cooled in a heat exchanger to 30°C and it was fed to the cryogenic section. In the cryogenic module, air was compressed to 6.1 bar in the 4-section compressor with interstage cooling to 30°C. The pressure ratio in each section was the same and the isentropic efficiency was assumed at 0.9. Detailed assumptions and input data for the analysis are presented in [18]. A scheme of the analyzed installation is shown in Fig. 3.

The energy intensity of a hybrid installation can be determined from Eq. (3):

$$e_{\text{MEM-CRYO}} = \frac{N_{\text{el,VENT}} + N_{\text{el,VP}} + \sum_i N_{\text{el,C}} - N_{\text{el,T}}}{n_{O_2} \cdot (Y_{O_2}) \cdot M_{O_2}} \quad (3)$$

In the first stage of calculations, the influence of different parameters on the energy consumption of the membrane installation was determined. Exemplary results presenting the characteristics of energy consumption of oxygen production in the hybrid installation depending on permeate pressure and membrane area are shown in Fig. 4. It can be seen, that proper selection of these parameters in a membrane module resulted in reduction of the energy consumption (as compared with a cryogenic installation) to a value of 0.206 kWh $kg^{-1}O_2$.

Although the energy consumption of the oxygen production in the hybrid installation was lower than in the case of the reference, cryogenic unit, further calculations were aimed to further lowering of this quantity. Consumption of energy for oxygen production in the membrane-cryogenic module can be reduced, among other, by:

- division of the vacuum pump into two sections,
- decreasing the cooling temperature between compressors and vacuum pump sections (e.g., to 20°C),
- assuming smaller flow resistance in the membrane module, and thus, reducing the pressure increase on the fan to 0.02 bar,
- increasing the selectivity coefficient from 10.65 to 40.

By applying the first three interventions, it was possible to reduce the energy consumption in the membrane-cryogenic separator to 0.190 kWh $kg^{-1}O_2$, what is shown in Fig. 5. It should be noted, that the selection of the appropriate pressure increase on the fan depends on the design of the specific membrane installation (pressure drop). Further reduction of the energy consumption of oxygen production installation can be expected with the development of membranes, especially ones of the increased selectivity towards oxygen. Research on such membranes development is intensively carried out in the world.

Fig. 6 illustrates the energy consumption of a hybrid oxygen separator as a function of the membrane selectivity coefficient α, which was changed in the range of 10.65 to 40. Line A demonstrates the results of the analysis run at the following assumptions: pressure increase at the fan equal to 0.05 bar, one-section vacuum pump, cooling between compressor sections and after vacuum pump to 30°C. The field where it is possible to get lower energy consumption by decreasing the temperature between sections of the machines (between curves A and B) is marked with grey color. Line B corresponds to the case, where the cooling temperature between sections of vacuum pump used in the hybrid installation was equal to

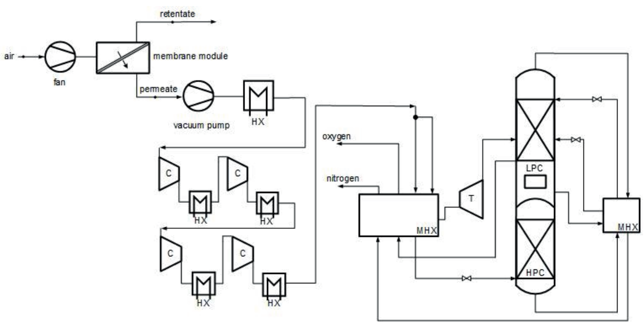

Fig. 3. Scheme of a hybrid membrane-cryogenic oxygen production installation (HX – heat exchanger, C – compressor, MHX – multistream heat exchanger, T – turbine, LPC – low-pressure column, HPC – high-pressure column).

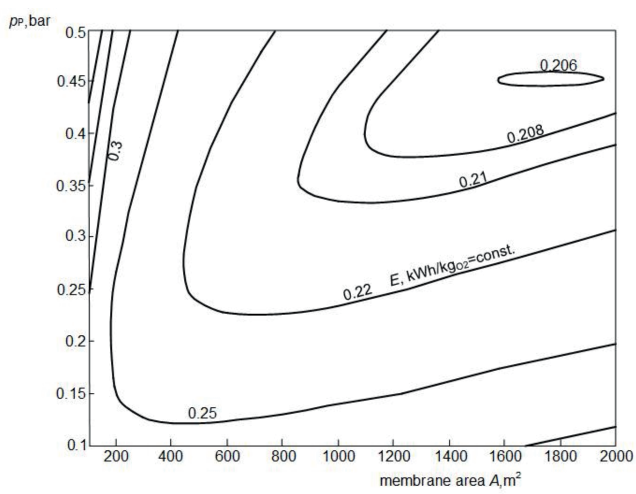

Fig. 4. Energy consumption of the membrane-cryogenic installation as a function of permeate pressure and membrane area in the reference unit.

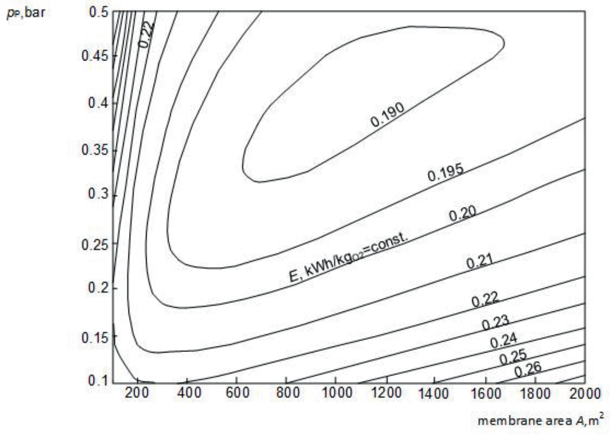

Fig. 5. Energy consumption of the membrane-cryogenic installation as a function of permeate pressure and membrane area in the system with reduced energy consumption.

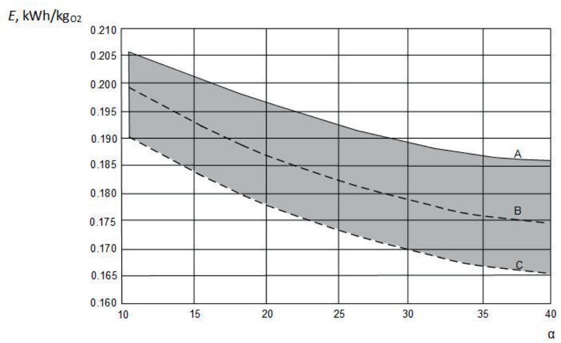

Fig. 6. The energy consumption of membrane-cryogenic oxygen plant as a function of selectivity coefficient α.

20°C. The area between curves B and C presents the range of energy demands, which were obtained by reduction of the pressure across the fan at the inlet to the membrane installation. Curve C illustrates the results of calculations performed under following assumptions: cooling temperature between sections of all machines in oxygen separator equal to 20°C and pressure increase caused by the fan at 0.02 bar. The minimum energy consumption achieved through these interventions for the coefficient α equal to 40, amounted to about 0.165 kWh kg^{-1}O_2.

5. Efficiency of electricity production in the coal unit

Further analyses were conducted for a 600-MW oxy-type coal unit integrated with a membrane-cryogenic oxygen plant and a carbon dioxide purification installation. In this system, a pulverized bed boiler working in the oxy-combustion technology with live steam parameters at 654.9°C/31.1 MPa and reheated steam at 672.4°C/6.15 MPa was used. The steam was directed to the turbine installation consisting of a high, medium and low-pressure turbines (HP, MP, LP) and seven regenerative heat (RH) exchangers. A mixture of oxygen and flue gases was directed to the boiler as an oxidant. Oxygen was produced in the hybrid air separator with a final purity

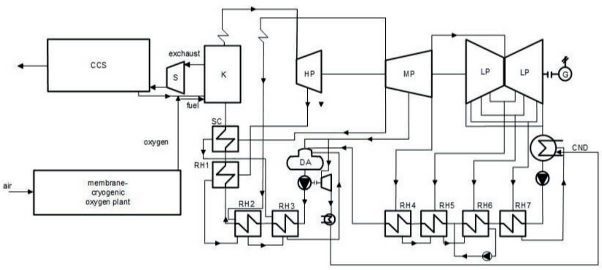

Fig. 7. Scheme of the oxy-type coal unit with membrane-cryogenic oxygen plant and CCS installation.

of 95% O_2 and fed to the boiler, after its mixing with recirculated CO_2. Flue gases from the boiler were purified in the CO_2 sequestration system. This installation consisted of a drying section and a physical separation proceeding at a low temperature. The flue gas treated by this method contained about 95% of CO_2, then it was compressed to 150 bar and it can be directed into the pipeline system (for transport). The schematic diagram of the analyzed coal unit is presented in Fig. 7.

Among the most important thermodynamic evaluation indices, net efficiency of electricity generation and auxiliary power rate of different technological installations can be enumerated.

The net efficiency of electricity generation in the analyzed coal unit is determined by Eq. (4):

$$\eta_{\mathrm{el,N}} = \frac{N_{\mathrm{el,g}} - N_{\mathrm{el,PW}}}{\dot{m}_{\mathrm{w}} \cdot W_{\mathrm{d}}} \tag{4}$$

The electric power required to drive auxiliary devices in the power plant ($N_{\mathrm{el,PW}}$) is a sum of the electric power of all auxiliary systems operating in this coal unit: steam cycle $N_{\mathrm{el,SC}}$, oxygen plant $N_{\mathrm{el,MEM\text{-}CRYO}}$, pulverized bed boiler $N_{\mathrm{el,PB}}$ and carbon capture installation $N_{\mathrm{el,CCS}}$:

$$N_{\mathrm{el,PW}} = N_{\mathrm{el,SC}} + N_{\mathrm{el,PB}} + N_{\mathrm{el,MEM\text{-}CRYO}} + N_{\mathrm{el,CCS}} \tag{5}$$

Eq. (4), after modification, can be rewritten as:

$$\eta_{\mathrm{el,N}} = \eta_{\mathrm{SC}} \cdot \eta_{\mathrm{B}}(1-\delta) \tag{6}$$

where δ is auxiliary power rate, calculated for each technological installation or for the whole plant as a ratio of auxiliary power (of a given installation or plant) and gross power of the power plant.

Table 1 presents the thermodynamic evaluation indicators for the analyzed oxy-combustion power plant. It should be pointed out, that the auxiliary power of oxygen plant (energy consumption of oxygen production) is the most important factor, which affects the net efficiency of the coal unit, thus, all operations aiming to reduce this quantity are justified.

The efficiency of electricity generation can be improved by integrating ASU and carbon dioxide capture system with steam turbine cycle of the analyzed coal unit. For this purpose, waste heat generated in these installations may be used

Table 1
Thermodynamic evaluation indicators of the oxy-type power plant

Auxiliary power of steam cycle ($N_{el,SC}$), MW	19.6
Auxiliary power of boiler ($N_{el,B}$), MW	12.23
Auxiliary power of CCS ($N_{el,CCS}$), MW	58.51
Auxiliary power of membrane-cryogenic oxygen plant ($N_{el,MEM\text{-}CRYO}$), MW	73.64
Total auxiliary power of power plant ($N_{el,PW}$), MW	163.98
Total auxiliary power rate of power plant ($\delta_{el,PW}$)	0.273
Thermal efficiency of boiler (η_B), %	94.16
Net efficiency of coal unit ($\eta_{el,N}$), %	35.55

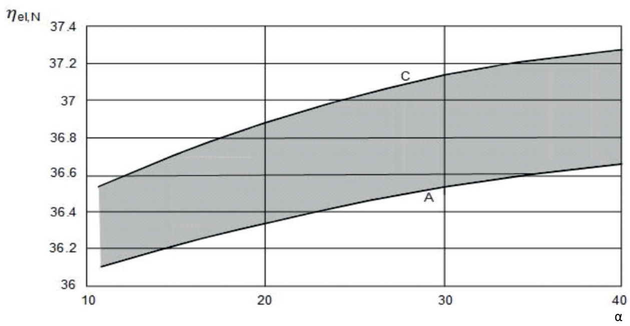

Fig. 8. The influence of the membrane selectivity coefficient α on the net efficiency of the analyzed power plant.

to heat the condensate. This heat can be obtained in large amounts, but it is of poor quality and thus, it can be only used to replace the low-pressure RH exchangers.

The results of calculations show that the replacement of two heat exchangers, RH7 and RH6, enabled to generate additional 6.98 MW of electric power, which caused an increase of the net efficiency of the coal unit to 36.12%. Computational methods are described in details in [18–21].

Reduction of the energy consumption of the membrane-cryogenic oxygen plant and improvement of the membrane separation properties (permeability, selectivity) influence the net efficiency of the whole power plant. The results of calculations of this parameter as a function of the membrane selectivity coefficient α are presented in Fig. 8. The assumptions for lines A and C are the same as it was in the case of Fig. 6.

The improvement of the selectivity coefficient α resulted in the increase of the net efficiency of electricity generation. It was associated with a decreasing value of energy consumption in the membrane-cryogenic oxygen plant. The area of the achievable unit efficiency is indicated by a grey color between curves A and C. In general, lower efficiency was achieved for lower values of selectivity of the membrane in a hybrid oxygen separator. For the membrane selectivity coefficient equal to 40, the net efficiency of the power plant could reach 37.27%.

6. Economic analysis of the coal unit integrated with the membrane-cryogenic oxygen plant

One of the indicators of economic effectiveness, most often used in the analysis concerning power systems, is the net present value (NPV) method [16]:

$$\mathrm{NPV} = \sum_{t=0}^{t=N} \frac{\mathrm{CF}_t}{(1+r)^t} \tag{7}$$

The NPV indicator depends on the stream of the net cash flows CF_t in the consecutives years of operation of power plants and the discount rate. The investment is regarded as economically profitable for the condition NPV > 0, while for the case NPV = 0 investment is on the border of economic efficiency.

Another indicator of economic efficiency evaluation, which is often used in analyses of power systems, is the break-even price of electricity. It is determined for the condition NPV = 0, and calculated from Eq. (8):

$$C^{\mathrm{gr}} = \frac{\sum_{t=0}^{t=N} \frac{[J + (C_{\mathrm{OP}} + T_{\mathrm{in}} + C_{\mathrm{wo}}) - A - L}{(1+r)}}{\sum_{t=0}^{t=N} \frac{(1-\delta)\cdot N_{\mathrm{el,g}} \cdot \tau_{\mathrm{el}}}{(1+r)^{\mathrm{t}}}} \tag{8}$$

The economic analysis was carried out for two variants of the coal unit, with a gross power equal to 600 MW:

- the reference system with the air-fired pulverized bed boiler without oxygen plant and CCS; this power plant has the same steam parameters and gross power as oxy-type unit;
- coal unit with oxy-type pulverized bed boiler integrated with the membrane-cryogenic oxygen production installation and CCS system; for this case it was assumed that the lifetime of membrane was 5 years.

In Table 2, the main assumptions for the economic analysis of the analyzed variant of the air-fired and oxy-combustion power plant (with hybrid ASU) are summarized. In the analysis, it was assumed, that the EU emission Trading Scheme was in force, thus, the emission allowances had to be bought for each Mg of emitted carbon dioxide. Detailed assumptions for the economic analysis are presented in [19].

The break-even price of electricity was determined on the basis of the assumptions for the two analyzed cases and the results were as follows:

- reference unit: 63.4 € MWh^{-1},
- coal unit with the membrane-cryogenic air separation plant, where the lifetime of membranes was 5 years: 71.5 € MWh^{-1}.

For the oxy-type coal unit with the membrane-cryogenic oxygen separator, membranes with different selectivity coefficients α were considered. The coefficient α was changed in the range from 10.65 to 40. The change of oxygen and nitrogen selectivity coefficient induced changes in the membrane module, that is, the pressure on the permeate side, the molar concentration of oxygen in the permeate and the membrane surface. The membrane surface influences the cost of membrane module.

Table 3 summarizes the results of calculations of the investment costs of the oxy-type coal unit for membranes with different values of the selectivity coefficient.

Fig. 9 shows a change of break-even price of electricity as a function of the selectivity coefficient. For lines A and C, the same assumptions as those for Fig. 6, were adopted.

Table 2
Main assumptions of the economic analysis

Specification	Value
Annual working time, h a^{-1}	7,500
Gross power of the power plants, MW	600
Unit investment costs of the reference plant, € kW^{-1}_{gross}	1,365
Unit investment costs on the unit with the membrane-cryogenic installation, € kW^{-1}_{gross}	1,944
Construction time, y	3
Share of own means, %	20
Share of commercial credit, %	80
Actual interest of commercial credit, %	6
Income tax rate, %	19
Payback time of commercial credit, y	10
Exploitation time, y	20
Discount rate, %	6.2
Exploitation costs, € MWh^{-1}	5.8
CCS exploitation costs, € $MgCO_2^{-1}$	4.6
Coal price, € GJ^{-1}	2.29
	55
CO_2 emission allowances price, € Mg^{-1}	21.8
Pers. MW^{-1}_{gross}	0.4
Unit employment in the unit with cryogenic and hybrid air separator, pers. MW^{-1}_{gross}	0.5
Monthly salary including related costs, € $post^{-1}$ $month^{-1}$	1,190
Average depreciation rate, %	6.67

Variations of the break-even price of electricity along with the change of the membrane selectivity coefficient for the cases, where the CO_2 emission allowances price is equal to 10.9 € $Mg^{-1}CO_2$ and 0 € $Mg^{-1}CO_2$, respectively, are shown in Fig. 9.

The area of potential reduction of the break-even price of electricity under the assumptions made for the hybrid oxygen plant is indicated in Figs. 9 and 10 by the grey color. The minimum value of the break-even price of electricity could be achieved for curve C and for the cost of CO_2 emission equal to 0 € $Mg^{-1}CO_2$. It amounted to 64.7 € MWh^{-1}.

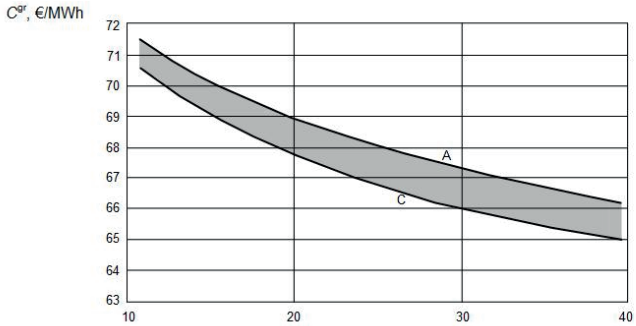

Fig. 9. The influence of changes of selectivity coefficient α on the break-even price of electricity.

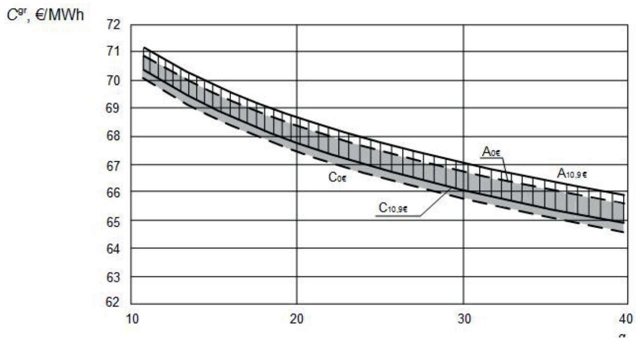

Fig. 10. The influence of changes of selectivity coefficient α on the break-even price of electricity for CO_2 emission allowances price at 10.9 € $Mg^{-1}CO_2$ ($A_{10,9€}$, $C_{10,9€}$) and 0 € $Mg^{-1}CO_2$ ($A_{0€}$, $C_{0€}$).

Table 3
Main assumptions for economic analysis of membranes with different selectivity coefficient

Selectivity O_2 N_2^{-1}	Oxygen permeability coefficient, m^3_N $(m^2{\cdot}h{\cdot}bar)^{-1}$	Pressure on the permeate side, bar	Oxygen concentration in the permeate, %	Membrane area, mln m^2	The cost of membrane module, € kW^{-1}_{gross}	Cost of oxy type unit, € kW^{-1}_{gross}
10.65	3.111	0.46	37	2.660	168	1,944
15	4.383	0.40	42	2.005	130	1,901
20	5.844	0.35	47	1.578	105	1,871
30	8.766	0.30	53	1.173	82	1,842
40	11.688	0.20	68	0.582	51	1,802

7. Summary

In this paper, the implementation of a hybrid membrane-cryogenic oxygen plant for oxygen production for a coal unit with oxy-type pulverized bed boiler was analyzed. The results of the energy consumption analysis depending on the conditions assumed in the membrane module, that is, permeate pressure and membrane area, were discussed. The proper selection of these parameters can reduce the electric power required to drive devices in the oxygen plant and allows reaching the minimum energy consumption at 0.206 kWh $kg^{-1}O_2$, which is a lower value than one of the reference cryogenic oxygen separator (0.222 kWh $kg^{-1}O_2$). Further reduction of energy consumption in a hybrid oxygen plant, as it was shown in this paper, can be realized with the following methods: splitting the vacuum pump in sections, reducing the cooling temperature between the sections of the devices to 20°C, using a membrane module with lower values of the flow resistance and increasing the selectivity ratio of the membrane. The minimum energy consumption, which could be achieved, amounted to 0.165 kWh $kg^{-1}O_2$ for selectivity coefficient equal to 40. It should be pointed out, that currently there are no membranes available for such separation parameters. The net efficiency of the analyzed power plant was equal to 35.55%. The efficiency of the power plant can be improved by thermal integration of the oxygen separator and CCS installation with steam turbine cycle and this method allowed obtaining net efficiency equal to 36.12%. For membrane selectivity coefficient at 40, the net efficiency of the unit equal to 37.3% could be achieved. The economic analysis was carried out for different values of the membrane selectivity coefficient α. For α equal to 40, the break-even price of electricity was the lowest, amounting approximately to 65 € MWh^{-1}.

Symbols

A — Depreciation, € a^{-1}
C_{OP} — Operating costs, €
C_{WC} — Change of the working capital, €
C_{wo} — Working capital
F — The cost of financing, € a^{-1}
J — Investment costs, €
L — Salvage value, €
$\dot{m}_w$ — Coal stream directed to the coal unit, kg s^{-1}
M — Oxygen molar mass, kg $kmol^{-1}$
nO_2 — Molar stream, kmol h^{-1}
$N_{el,C}$ — Electric power needed to drive the compressor, kW
$N_{el,g}$ — Gross electric power of power plant, MW
$N_{el,PW}$ — Electric power required to drive auxiliary devices in power plant, MW
$N_{el,VP}$ — Electric power required to drive the vacuum pump, kW
$N_{el,VENT}$ — Electric power required to drive the fan, kW
$N_{el,T}$ — Electric power obtained in the turbine, kW
p_F — Feed pressure, bar
p_P — Permeate pressure, bar
r — Discount rate
r_K — Discount of commercial credit
r_W — Interest of own capital
S — Revenues from sale, €
t — Consecutive year of consideration from the beginning of the construction system
T_{in} — Income tax, %
u_k — Share of credit in financial investment
W_d — Lower heating value of coal, kJ kg^{-1}
X_i — Component concentration in the feed
Y_i — Component concentration in the permeate
(YO_2) — Oxygen concentration in the final product

Greek symbols

η_B — Efficiency of pulverized bed boiler
η_{SC} — Efficiency of steam cycle
δ — Auxiliary power rate
τ_{el} — Annual working time

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