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Comparative study of oxygen separation using cryogenic and membrane techniques for nCO2PP

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Abstract:

Due to the intense use of coal and gas while producing electricity, carbon capture and storage technologies need to be developed. One of the perspectives is oxyfuel combustion. It is the easiest method in the light of subsequent capture and storage of carbon dioxide. Due to the lack of nitrogen in the substrate, there are no nitrogen oxides in flue gases. The main drawback of that method is the very high energy consumption of the oxygen production technology. These days well-known technologies are cryogenic distillation and pressure swing adsorption. There are also novel oxygen production techniques such as chemical looping air separation and membrane processes. In the paper, a comparison between cryogenic air distillation and membrane separation is taken into consideration. Energy consumption of the cryogenic air distillation is on average 250 kWh/ ton O_2. On the other hand, there is an oxygen transport membrane but this approach requires a heat source because the process takes place at very high temperatures. Produced oxygen is required for the concept of the negative CO_2 gas power plant (nCO2PP). The power cycle uses oxygen and sewage sludge gasification gas for the combustion process. The two mentioned earlier oxygen production installations were modelled and confronted with the needs of the nCO2PP. Obtained cumulative efficiencies of the nCO2PP cycles were 21.26% and 23.48% for the power cycle integrated with a cryogenic air separation station (depending on oxygen purity), and 24.89% and 24.59% for the cycle combined with oxygen transport membrane (depending on the membrane area). The power cycle consists of a gasifier, air separation unit, compressors, turbines, wet combustion chamber, spray ejector condenser, and a CCS installation. The nCO2PP cycle is equivalent to the Bioenergy with Carbon Capture and Storage idea, because of the use of sewage sludge as fuel and CO_2 capture.

Keywords:

Thermodynamic analysis; Oxy-combustion; Energy penalty; CCS; cryogenic ASU; oxygen transport membrane.

1. Introduction

The oxy-fuel combustion is supposed to be one of the remedies for global warming, next to pre-combustion and post-combustion technologies [1]. The use of oxygen as an oxidizer prevents the generation of nitrogen oxides and provides only water vapor and carbon dioxide in exhaust gases. It should be highlighted, that oxy-combustion is one of the Carbon Capture and Storage (CCS) technologies and it is said to be the most promising one for the power cycles fuelled with fossil fuels [2]. The oxygen is 21% of the atmospheric air, and its amount delivered to the combustion chamber is based on the combustion stoichiometry, which is approximately 18 – 20 tons of O2/ day for 1 MW of electric installed power [3], [4]. If the biggest Polish power plant "Bełchatów" would work with oxy-combustion technology it would require as much as 92 thousand to 102 thousand tons of O2 per day depending on the power output.

The presented paper refers to oxygen production for the needs of the "Negative CO_2 emission gas power plant" (nCO2PP) [5], which is a kind of bioenergy with carbon capture and storage (BECCS) power cycle. The nCO2PP is a cycle, which utilizes sewage sludge as fuel and works with the oxy-combustion process. In this work, cryogenic air distillation and oxygen transport membrane (OTM) were taken into consideration.

Cryogenic air separation is the most popular and developed way to produce oxygen for the needs of oxyfuel combustion [6-8]. This way of oxygen production also provides other gases, like nitrogen, argon, krypton, and xenon [9]. The technology of very low temperatures is used to generate methane and helium from natural gas or in hydrogen production from coke oven gas [6]. It is based on the use of boiling points of air components to separate them. The air must be cooled first and then transported to rectification columns where is separated [10].

The second oxygen production method is the one using an oxygen transport membrane. The separation process is able to be carried out because of the electrochemical mechanisms and diffusion [11]. There are two

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types of designs of oxygen production with the OTM method that can be highlighted, namely the three-end and four-end ones. The first one is about creating a vacuum on the permeate side of the membrane. The four-end is about introducing recirculated exhaust gases in counter-current on the permeate side of the membrane in case to provide the driving force [11, 12]. Oxygen transport membranes are made of two main groups of materials, that is perovskite and fluorite [13]. The third technology of oxygen production is pressure swing adsorption [14, 15], but it is not considered in this work.

The aim of this paper is to compare two technologies of oxygen production (based on air separation) for the requirements of the nCO2PP and check their impact on cycle efficiency. In this case, two models of oxygen production stations have been examined and integrated with the nCO2PP model. All analyses have been carried out using the Ebsilon software [16].

2. The power cycle

2.1. Negative emission CO_2 gas power plant

The oxy-combustion technology is said to be the best solution to capture and store carbon dioxide from power plants [17]. Over the years many power cycle installations with oxy-combustion technology have been proposed [18-20]. The negative carbon dioxide emission gas power plant means that the electricity is produced with negative carbon dioxide emission in the total balance of emissions. Emission is negative because the power plant uses sewage sludge as fuel and an oxy-fuel method to capture CO_2. If only one of the mentioned approaches was used, only a zero-emission power cycle would be an outcome. The scheme of the nCO2PP is shown in Figure. 1.

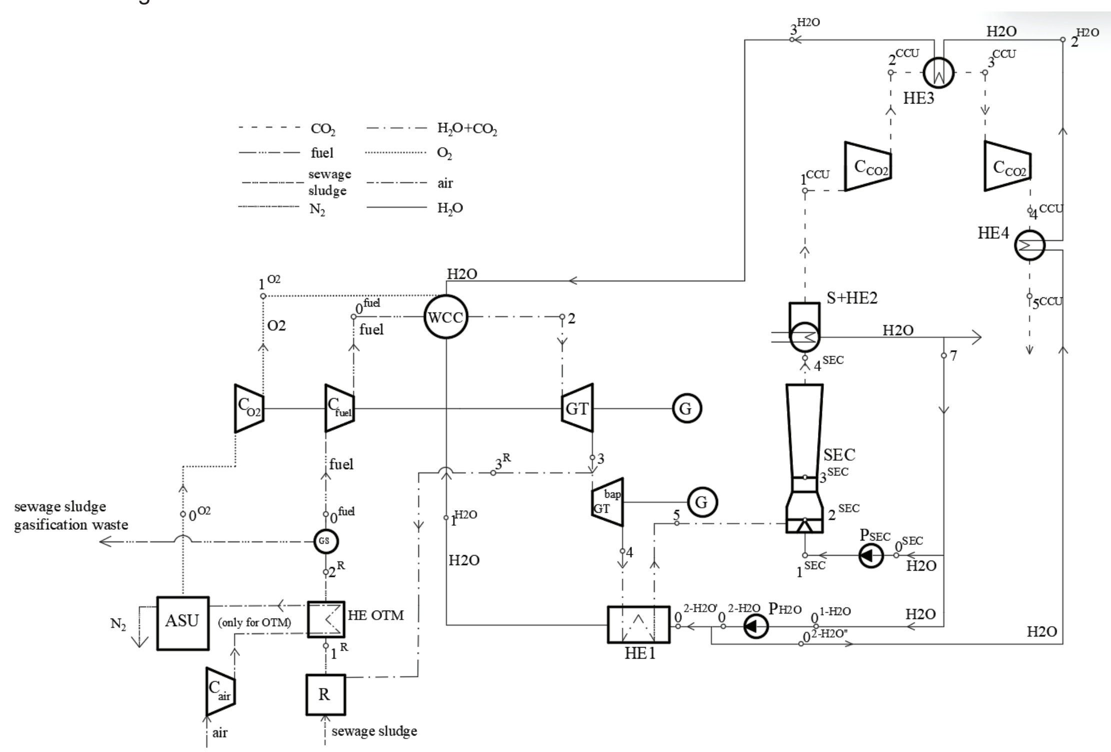

Figure. 1. The negative emission CO2 gas power plant (nCO2PP) integrated with gasification and oxygen transport membrane type of ASU, where: C_{air} – air compressor, C_{O2} – oxygen compressor, C_{fuel} – fuel compressor, WCC – wet combustion chamber, GT – gas turbine, GT^{bap} – low-pressure turbine, HE1 – heat exchanger 1, SEC – spray-ejector condenser, G – generator, P_{H2O} – water pump, P_{SEC} – SEC pump, S+HE2 – separator connected with heat exchanger 2, C_{CO2} – CO_2 compressor, HE3 – heat exchanger 3, HE4 – heat exchanger 4, HE OTM –heat exchanger for OTM separation, GS – gas scrubber, R – gasifier, ASU – air separation unit.

The nCO2PP cycle consists of an air separation unit (ASU), gasifier (R), carbon capture and storage installation (CCS), and the main part of the installation. The system is equipped with two compressors. The first one transports oxygen (C_{O2}), whereas the second one is for fuel transport (C_{fuel}). The cycle also consists of the high-pressure gas-steam turbine (GT – expansion from 10.5 bar to 1 bar), low–pressure turbine (GT^{bap} – expansion from 1 bar to 0.078 bar), wet combustion chamber (WCC – with temperature 1100℃), and generator (G). The main heat exchanger (HE1) heats the water supplied to the WCC with exhaust gases. The spray–ejector condenser (SEC) is a crucial device in the process of condensation of steam from a mixture of

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CO_2+H_2O. A CCS installation consists of two compressors (C_{CO2}), two heat exchangers (HE3, HE4), and a heat exchanger connected with a water separator (S+HE2). The water pump (P_{H2O}) increases the pressure of water to a value of 10.5 bar, which is supplied to the WCC [5].

The initial nodes in the cycle can be established when fuel and oxygen compressors (C_{fuel}, C_{O2}) start transporting fluids to the combustion chamber (WCC). In WCC the combustion process takes place which creates a mixture of CO_2 and H_2O. Fuel and oxygen are necessary substrates, however, due to the high temperature of the processes there is injected water as a cooling medium to attain a temperature around 1100℃. Injection of the cooling medium is obligatory, because of the high temperature of stochiometric combustion, which can increase even to 3000 K as the effect of the oxy-combustion process. Additionally, the extra mass flow of water (nodal points 2^{H2O}, 3^{H2O}) contributes to the increase of the cycle efficiency, which is dependent on amount of regenerated heat. After the process in the WCC exhaust expands in the turbines (GT, GT^{bap}). Afterward, exhaust gases are used to heat water which is transported to the WCC in the regenerative heat exchanger (HE1). A part of the exhaust stream is directed to the gasification reactor (R) (or gasifier) and it is used in the gasification process. The spray-ejector condenser (SEC) intakes flue gases from the heat exchanger (HE1). Provided is also water, which is a motive fluid in the SEC with the pump (P_{SEC}). The presence of motive water, which breaks up into droplets and a mixture of steam and carbon dioxide enables the condensation process to take place. A mixture of water and carbon dioxide leaving the SEC goes to the separator connected with the heat exchanger (S+HE2). In the separator, water is isolated and directed to pumps (P_{SEC}, P_{H2O}). Subsequently, it is used as the motive fluid in SEC or as a coolant in the combustion chamber. The carbon dioxide is directed to the compressor (C_{CO2}), and then to the heat exchanger (HE3). It ought to be mentioned that in the air separation process with a membrane, the compressed air takes heat from fuel at the additional heat exchanger (HE OTM) downstream of the outlet of the gasifier. It is profitable because the oxygen production process with OTM needs to be carried out at a very high temperature, and fuel transported to the combustion chamber needs to be cooled before the fuel compressor (C_{fuel}).

2.2. Air separation units

As it was mentioned, two ways of oxygen production from the air were taken into consideration: cryogenic air distillation and oxygen transport membrane. Diagrams of them are shown in Figure. 2. For modelling using the Ebsilon software the cryogenic air separation unit is developed of an air compressor C_{air}, a pre-cooler PC, and two rectification columns RCI and RCII. In the separation process, the air is compressed to 5.8 bar, cooled in the pre-cooler, transported into the columns, and then separated into oxygen (O2), high-purity nitrogen (hN2), and low-purity nitrogen (lN2).

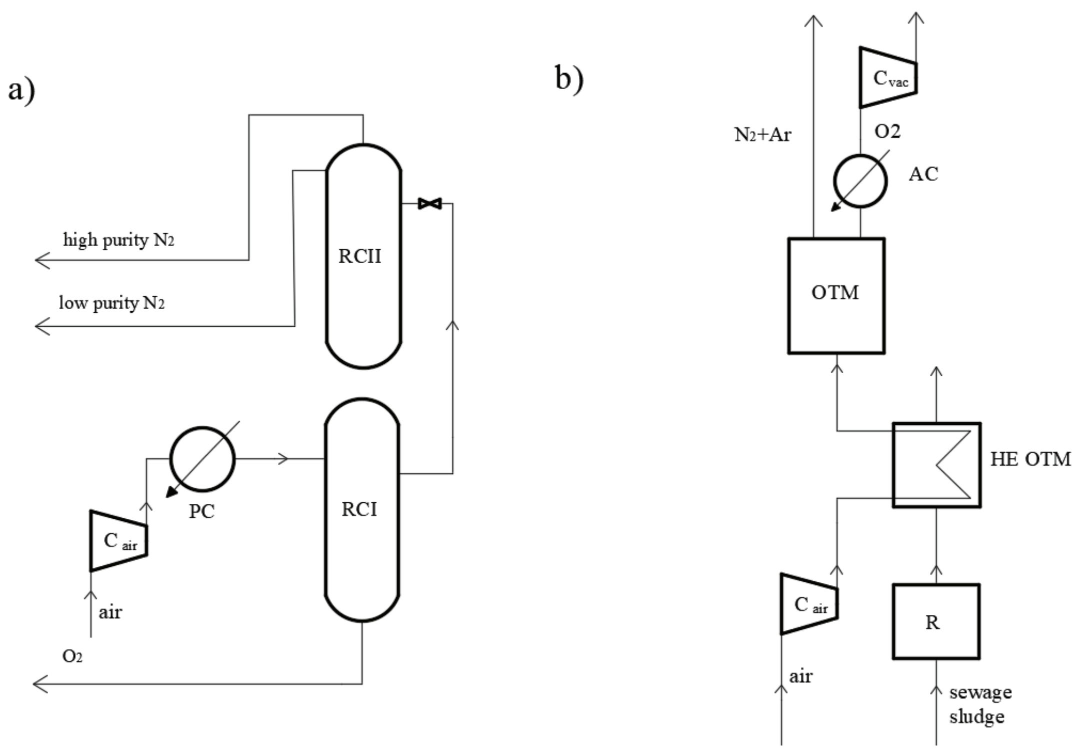

Figure. 2. Diagrams of oxygen production stations a) cryogenic b) oxygen transport membrane, where:

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C_{air} – air compressor, PC – pre-cooler, RCI – column I, RCII – column II, R – gasifier, OTM – oxygen transport membrane, HE OTM – heat exchanger, AC – after-cooler, C_{vac} – vacuum pump.

The membrane separation unit consists of an air compressor C_{air}, a heat exchanger HE OTM, an after-cooler AC, a vacuum pump C_{vac}, and a membrane OTM. In this process, the proper oxygen partial pressure ratio at both sides of the membrane is set. These ratio values are 1.034 and 1.330 (depending on the membrane area), then heated to 740 ℃ in the HE OTM, separated in the membrane, and then cooled in AC before transporting to the oxygen compressor and the combustion chamber.

The main difference between the OTM method and the cryogenic ASU is that in the cryogenic separation air is cooled down in the pre-cooler after compression, whereas with the OTM, the air after compression must be heated to the correct temperature values for the electrochemical reaction to take place.

3. Methodology

The analyses have been carried out in the Ebsilon software, which uses mass and energy balance equations. Additionally, real gas correction equations such as the Peng-Robinson or the Redlich-Kwong equation can be set. The software predefined models are clearly expressed by thermodynamic tables for steam.

3.1. Efficiency calculation

The gross efficiency and the net efficiency have been calculated according to Eq. (1) and (2)

$$\eta_g = \frac{N_t}{\dot{Q}_{CC}} \tag{1}$$

where $N_t$is a combined power of turbines in kW and $\dot{Q}_{CC}$ is a chemical energy rate of combustion in kW.

$$\eta_{net} = \frac{N_t - N_{CP}}{\dot{Q}_{CC}} \tag{2}$$

Where $N_{CP}$is power needed for cycle own needs in kW and can by expressed by Eq. (3).

$$N_{CP} = N_{ASU} + N_{C_{fuel}} + N_{C_{O2}} + N_{P_{H2O}} + N_{P_{SEC}} + N_{C_{CCS}} \tag{3}$$

Where N_{ASU} is power for oxygen production, $N_{C_{fuel}}$ is power for fuel compressor, $N_{C_{O2}}$ is power for oxygen compressor, $N_{P_{H2O}}$is power for water pump, $N_{P_{SEC}}$ is power for SEC and $N_{C_{CCS}}$ is power for CCS compressors needs. All mentioned terms are expressed in kW.

Additionally, cumulative cycle efficiency which is a product of the net efficiency of the power cycle (η_{net}) and gasification process efficiency (η_{R_H}), has been calculated. The gasification process inside the gasifier was not calculated in this work but its efficiency has been taken from other work regarding nCO2PP [21]. The cumulative efficiency is presented in Eq. (4):

$$\eta_{cum} = \eta_{R_H} \cdot \eta_{net} \tag{4}$$

where gasification process efficiency (η_{R_H}) according to the literature [21] is equal to η_{R_H} =86.52% for the nCO2PP cycle.

3.2. Oxygen transport mechanism in the membrane

Oxygen permeation in the membrane is dependent on mass diffusion and electrochemical factors. Oxygen flux through the membrane can be formulated with the Wagner equation, which is presented in Eq. (5) [11]

$$j_{O2} = C_{wagner} \cdot \frac{T_m}{d_m} \cdot e^{\left(\frac{-K_{wagner}}{T_m}\right)} \cdot \ln \frac{P_{O2feed}}{P_{O2perm}} \tag{5}$$

Where j_{O2} is oxygen permeation rate in mol/(m^2*s), T_m process temperature in K, d_m is membrane thickness in m, P_{O2feed} is pressure at the feed steam side in bar, P_{O2perm} is pressure at the permeate side in bar, C_{wagner} is a constant dependent on material in mol/(m*s*K), and K_{wagner} is a constant expressed in K.

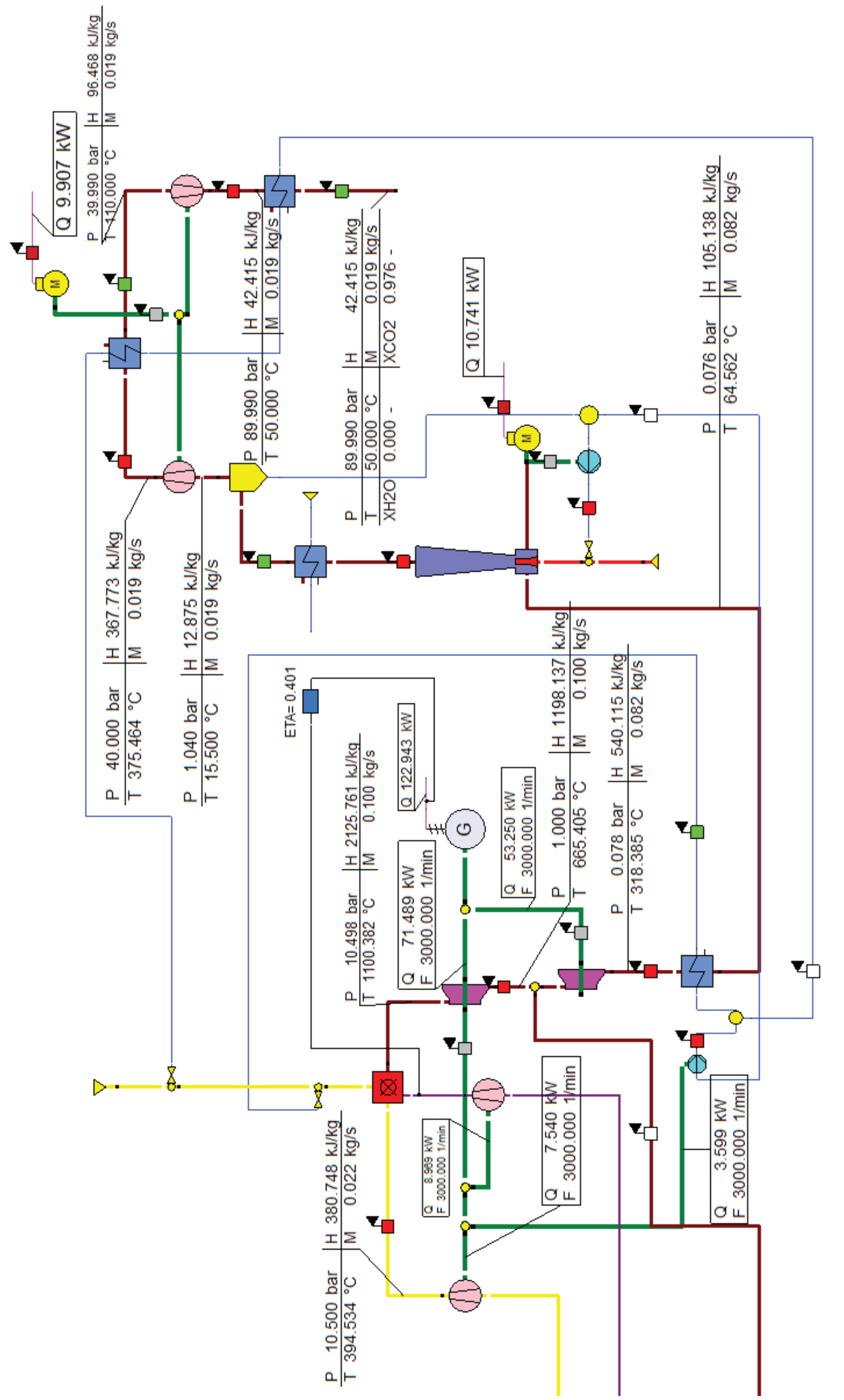

Figure. 3. The setup of the nCO2PP model in the Ebsilon software for the cryogenic case (without the ASU model) [22]

Coefficients K_{wagner} and C_{wagner} are dependent on the membrane material and they values are determined experimentally but in this case values from the literature were taken [11, 12].

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The presented formula is an Arrhenius approach to Wagner equation, which assumes ionic conductivity is more important in the permeation process in the membrane than the electron based conductivity [11].

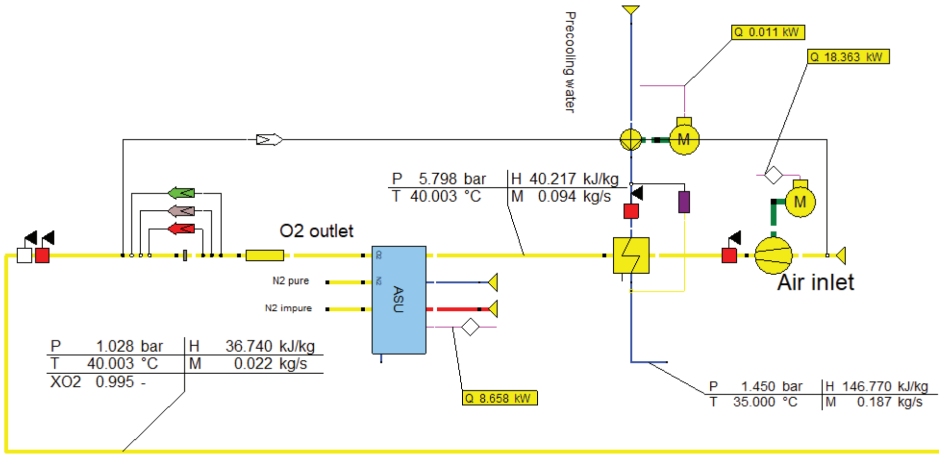

Figure. 4. The setup of the cryogenic ASU model in the Ebsilon software for 99.5% oxygen purity

3.3. Energy penalty and emissivity

For both oxygen production techniques, an important parameter is the energy penalty of oxygen production, which is expressed by the Eq. (6):

$$e_{pen} = \frac{N_{ASU}}{\dot{m}_{O2} * 3600} \tag{6}$$

where N_{ASU} is power for the needs of oxygen production expressed in kW and $\dot{m}_{O2}$ is the produced oxygen mass flow expressed in kg/s.

As the considered cycle name says, an essential factor is the emission potential (Eq. (7)) of the whole system, which can be defined with Eq. (7) [23, 24]:

$$eCO_2 = R\frac{\dot{m}_{4-CO_2}}{N_t - N_{cp}}3600 \tag{7}$$

where $\dot{m}_{4-CO2}$ is mass flow rate of carbon dioxide at the outlet of the CCS, R is a factor describing energy source as renewable energy (R for sewage sludge is 90% according to the Polish law [25]). Emission potential eCO_2 is expressed in $kgCO_2/(MWh)$.

The emission calculations should be carried out properly and carefully if the power cycle is integrated with the carbon capture and storage unit. If an energy source is only partly considered as a renewable source of energy, emissions should be multiplied by the factor that accounts for it. In this case, the relative emissions of carbon dioxide were multiplied by η_{net}. The relative emission is presented by Eq. (8).

$$\eta_{net} \cdot e_{CO_2} = \frac{N_t - N_{cp}}{LHV_{gas} \cdot \dot{m}_{0-fuel}} R \frac{\dot{m}_{4-CO2}}{N_t - N_{cp}} 3600 = R\frac{\dot{m}_{4-CO2}}{\dot{Q}_{CC}}3600 \tag{8}$$

Avoided eCO_2 for the negative emission power plant is a sum of emissions without CO_2 capture and the value of negative emissions obtained because of the application of renewable energy source [24].

4. Assumptions

For the purpose of calculations, several assumptions were made. The nCO2PP cycle uses sewage sludge as feedstock for gasification and fuel production. The combustion process is carried out with oxygen as the oxidizer. On top of the mentioned earlier, the following assumptions have been made in calculations:

- mixture of fuel and oxidant is stoichiometric,
- mass flow rate of exhaust gases is constant, and its value is 0.1 kg/s,

- temperature in the combustion chamber is constant and its value is 1100 ^oC,
- pressure in the combustion chamber is constant and its value is 10.5 bar,
- pressure after turbines GT and GT^{bap} are respectively 1 bar and 0.078 bar.

Calculations were carried out for two oxygen production stations. For cryogenic installation, two analyses dependent on oxygen purity were made, namely one for 99.5% (extremely high with higher energy penalty) purity and the second for 96% purity (accepted value for many technical processes). The air at the inlet to the cryogenic unit was compressed to 5.8 bar. For OTM solution also two analyses were made with constant oxygen purity at the level of 99.5%. However, one for 96 cm^2 membrane area and the second for 12 cm^2. Oxygen flux through the membrane is dependent on several features. The first one is a membrane thickness, which was set as 1 mm as in the literature [26]. The process temperature was set as 740℃, because of possibility of heating up in the heat exchanger after gasification process. Values of the mentioned coefficients K_{wagner} and C_{wagner} were taken from literature respectively as 6201 K and $1.004*10^{-6}$ mol/(m×s×K) [11, 12]. Syngas from sewage sludge gasification has the following composition: 13.31% CO, 5.12% H_2, 11.46% CH_4, 59.29% CO_2, 8.03% C_3H_8, and its LHV is 17.44 MJ/kg.

Other assumptions are included in Table 1.

Table 1. Assumptions for the thermodynamic cycle negative CO_2 gas power plant (nCO2PP) integrated with gasification and ASU

Parameter	Symbol	Unit	Value
Initial fuel temperature	t_{fuel}	ºC	50
Initial oxygen temperature	t_{O2}	ºC	15
Syngas fuel pressure before C_{fuel} compressor	p_{0-fuel}	bar	1
Oxygen pressure before C_{O2} compressor	p_{0-O2}	bar	1
Regenerative water pressure to WCC	p_{1-H2O}	bar	254.95
Exhaust vapor quality after HE1	x_5	-	0.999
Exhaust temperature after HE1, before SEC	t_5	ºC	62.77
CO_2 pressure after compressor C_{CCU1}	p_{2-CCU}	bar	40
CO_2 pressure after compressor C_{CCU2}	p_{4-CCU}	bar	90
H_2O temperature after HE4	t_{2-H_2O}	ºC	91.67
CO_2 temperature after HE3	t_{3-CCU}	ºC	110
Water vapor from Separator in 1^{CCU} mixed with CO_2 vapor	-	%	100% humid
Pressure after GT^{bap}	p_4	bar	0.078
Temperature after SEC	t_6	ºC	18.03
Turbine GT, internal efficiency (η_i)	η_{iGT}	-	0.89
Turbine GT^{bap}, η_i	$\eta_{iGT-bap}$	-	0.89
Fuel compressor C_{fuel}, η_i	$\eta_{iC-fuel}$	-	0.89
Oxygen compressor C_{O2}, η_i	η_{iC-O2}	-	0.87
Water pump P_{H2O}, η_i	η_{iP-H2O}	-	0.43
Water pump P_{SEC}, η_i	η_{iP-SEC}	-	0.80
CO_2 compressor C_{CO2-1}, η_i	$\eta_{iC-CO2-1}$	-	0.85
CO_2 compressor C_{CO2-2}, η_i	$\eta_{iC-CO2-2}$	-	0.85
Mechanical efficiency for all devices	η_m	-	0.99
Gasification process efficiency	η_{R_H}	-	0.8652

5. Results

In the course of calculations four scenarios were considered, i.e.:

- cryogenic air separation with 99.5% oxygen purity,
- cryogenic air separation with 96% oxygen purity,
- oxygen transport membrane separation with 96 cm^2 membrane area,
- oxygen transport membrane with 12 cm^2 membrane area.

In all cases exhaust mass flow after the combustion chamber was 100 g/s, and the temperature in the combustion chamber was 1100℃. Also in all cases pressure in the combustion chamber was 10.5 bar. Start values of fluids (air at the inlet of the air compressor and fuel at the inlet to gasifier) were set as 1 bar pressure and 15℃ temperature. Between two turbines GT and GT^{bap} is a bleed stream for transporting part of the exhaust to the gasifier, and its pressure is 1 bar. All the results are shown in Table 2. In the first two columns on the left side are the results for nCO2pp with different oxygen purities produced in cryogenic air separation

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unit. In the second two columns are presented results for nCO2pp with oxygen transport membrane with two different membrane areas. In Table 3 results of respective emissions are provided.

Table 2. Results of power output and efficiency of the analyses for all cases

			nCO2pp with cryogenic ASU		nCO2pp with OTM	
			oxygen purity 99.5%	oxygen purity 96%	membrane area 96 cm^2	membrane area 12 cm^2
Mass flow at the outlet of the WCC	m_2	g/s	100.00	100.00	100.00	100.00
Exhaust temperature at the outlet of the WCC	t_2	℃	1100.00	1100.00	1100.00	1100.00
Oxygen purity		%	99.50	96.00	99.50	99.5
Turbine bleed pressure		bar	1.00	1.00	1.00	1.00
Turbine power output	N_t	kW	143.05	143.68	144.54	144.61
Power for ASU/OTM needs	N_{ASU}	kW	27.03	18.97	14.00	14.81
Power for own needs	N_{CP}	kW	67.79	60.62	56.66	58.17
Fuel heat	LHV	kW	306.27	306.08	305.44	304.17
Gross efficiency	η_g	%	46.71	46.94	47.32	47.54
Nett efficiency	η_{net}	%	24.57	27.14	28.77	28.42
Cumulative efficiency	η_{cum}	%	21.26	23.48	24.89	24.59
Energy penalty	e_{pen}	kWh/kgO_2	0.346	0.242	0.179	0.190

Table 3. Results of emissions for all analyzed cases

			nCO2pp with cryogenic ASU		nCO2pp with OTM	
			oxygen purity 99.5%	oxygen purity 96%	membrane area 115.11 m^2	membrane area 300 m^2
Emission of CO_2	eCO_2	$kgCO_2/MWh$	-861.05	-741.15	-700.51	-712.20
Relative emissivity of CO_2	$\eta_{net} \cdot e_{CO_2}$	$kgCO_2/MWh$	-211.58	-201.12	-201.54	-202.39
Avoided CO_2 emission	Avoid CO_2	$kgCO_2/MWh$	1817.77	1564.65	1478.85	1503.52

6. Discussion

It was not obvious, which approach to oxygen production will be more appropriate for the negative CO_2 emission gas power plant. Both cryogenic distillation and oxygen transport membrane technologies are regarded as energy-consuming. In previous research, only cryogenic air separation was taken into consideration [22]. The nCO2pp power cycle has a characteristic gasifier that produces fuel at 967℃ [21]. This fact was a strong reason to investigate the oxygen transport membrane which needs a heat source.

Calculations indicate that net efficiencies of the nCO2PP for the cryogenic ASU for 99.5% and 96% oxygen purities are 24.57% and 27.14%. Taking into account a gasifier efficiency which was 86.52%, cumulative efficiencies values for the cycle with cryogenic ASU are 21.26% and 23.48% for higher oxygen purity and lower oxygen purity, respectively. It was similar to the cycle integrated with OTM. The nCO2PP reached higher efficiency when the OTM area was larger. For 96 cm^2 membrane area net efficiency and cumulative efficiency were 28.77% and 24.89%. For nearly six times smaller membrane area of 12 cm^2, these efficiencies were 28.42% and 24.59%. It is worth mentioning that by comparing cryogenic ASU (99.5% oxygen purity) and membranes, efficiency savings can be obtained. For 96 cm^2 of membrane area, it is 4.2%, and for 12 cm^2 is 3.85%. In [12] Portillo got 5% efficiency saving comparing these two technologies. Undeniably is the fact, that OTM ASU is thermally integrated with the nCO2PP, and the membrane does not require a heat source from the outside. All heat for air heating is taken from the gasification process, so it is internal cycle heat. It is very possible that the OTM solution would not be effective if there was a need to supply the heat source from the outside.

According to the results, the power demand for cryogenic ASU is 18.89% and 13.20% of the cycle generated power, respectively for 99.6% oxygen purity and 96% oxygen purity. According to the literature, cryogenic ASU should be responsible for 6-7% power loss for industrial solutions [27]. For lower stream rates, the energy requirement of the ASU becomes significantly higher, especially for demonstration and laboratory solutions. Therefore, this study considers a different solution, namely OTM. On the other hand, oxygen transport membrane unit power requirements are 9.69% and 10.24% of the generated power, respectively for 96 cm^2 membrane area and 12 cm^2 membrane area. It is very visible that power requirements for OTM are strongly dependent on the membrane area. It is similar to membrane thickness, air temperature, and membrane material [11, 12, 26].

An important thing is also the power needed to produce oxygen unit. To ensure a stoichiometric combustion process, to the combustion chamber 0.0217 kg/s oxygen mass flow was transported in all four cases. Obtained power consumption values for cryogenic ASU are 0.346 kWh/kgO_2 and 0.242 kWh/kgO_2 for 99.5% oxygen purity and 96% oxygen purity. It can be said those values are possible, especially in the light of the statement by Aneke [28] who says that for 99.9% oxygen purity the power consumption is 0.357 kWh/kgO_2, Tafone in [29] for 99.5% in his research assumes 0.370 kWh/kgO_2, and Fu C. in [4] says that for 95% purity the power consumption is 0.229 kWh/kgO_2. For OTM oxygen production 0.179 kWh/kgO_2 and 0.190 kWh/kgO_2 power consumption for 96 cm^2 and 12 cm^2 membrane area were obtained. Perhaps in this work, the membrane area doesn't occur to be a significant factor but if a bigger power cycle were considered, it would might be a very important thing for examination. According to every special case, it might be more effective to buy a smaller membrane but use more power during operation, or to buy a bigger membrane but use less power. Nevertheless, some researches show [30] that an infinite increase of the membrane area has rather a small effect on power saving.

Emissivity results are interesting. According to the results, cases with theoretically lower efficiency (cryogenic ASU with 99.5% oxygen purity and OTM with 12 cm^2 membrane area) reached a larger value of negative CO_2 emission. These two scenarios also obtained higher values of avoided CO_2 emission. It is because these two solutions have higher values of power for their own needs, which is important according to Eq. (7). Negative emission occurs due to the use of renewable energy source as fuel and using CCS installation. If there was only one of these two solutions, the power plant would be zero emissive.

7. Conclusions

The main novelty of the present work was the thermodynamic analysis of the nCO2PP cycle integrated with gasification and an OTM-type oxygen separation station. As the objective of the paper was to find an appropriate way of oxygen production technology for the negative CO_2 emission gas power plant (nCO2PP) it proved to be an uneasy task. Firstly, cryogenic air distillation was regarded to be a superior technology as it is recommended in most of the literature. However, the efficiency reductions obtained indicate that for such low flows of oxygen produced (as assumed in calculations), it makes more sense to buy it from industrial producers.

According to the obtained results, the oxygen transport membrane has better perspectives for the nCO2PP, especially because of a large amount of heat from the sewage sludge gasification process. To be sure of that, more factors such as membrane material, area, process temperature, and pressure difference at both sides of the membrane should be widely considered by CFD calculation. However, this is beyond the scope of this paper.

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Nomenclature

C_{wagner} constant dependent on the material, mol/(m×s×K)

d_m membrane thickness, mm

eCO_2 emissivity, kgCO_2/MWh

e_{pen} energy penalty, mWh/kgO_2

j_{O2} oxygen permetaion rate mol/(m^2×s)

K_{wagner} constant dependent on the material, K

LVH lower heating value, MJ/kg

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m mas flow, kg/s
N_{ASU} power for air separation needs, kW
$N_{C_{CCS}}$ power for CCS compressors needs, kW
N_{CP} power for own needs, kW
$N_{C_{fuel}}$ power for fuel compressor needs, kW,
$N_{C_{O2}}$ power for oxygen compressor needs, kW,
$N_{P_{H2O}}$ power for water pump needs, kW,
$N_{P_{SEC}}$ power for SEC pump needs, kW,
N_t combined turbines power, kW
P_{O2feed} pressure at the membrane feed stream side, bar
P_{O2perm} pressure at the membrane permeate stream side, bar
R factor describing energy source as renewable, -
t temperature, ℃
T_m process temperature, K
$\dot{Q}_{CC}$ chemical rate of combustion, kW

Abbreviations

AC after-cooler
ASU air separation unit
BCCS bioenergy with carbon capture and storage
C compressor
CCS carbon capture and storage
G generator
GS gas scrubber
GT gas turbine
HE heat exchanger
nCO2PP negative CO_2 emission gas power plant
OTM oxygen transport membrane
P pump
PC pre-cooler
R gasifier
RC rectification column
SEC spray ejector condenser
WCC wet combustion chamber

Greek Symbols

η_{cum} cumulative efficiency, %
η_g gross efficiency of the cycle, %
η_{net} net efficiency of the cycle, %
η_{R_H} gasifier efficiency, %

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