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Enhancing the overall efficiency of a lignite-fired oxyfuel power plant with CFB boiler and membrane-based air separation unit

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ABSTRACT

The power plant analyzed in this paper consists of the following systems: a steam turbine, a supercritical OXY-type circulating fluidized bed boiler fed with lignite characterized by a high moisture content (42.5%), and an air separation unit based on a 3-end type high temperature membrane and CO_2 compression installation. The steam turbine gross power is equal to 600 MW, and both the live and reheated steam parameters are equal to 600 °C/29 MPa and 620 °C/5 MPa, respectively. With the assumed constant gross power of the analyzed plant, the thermal efficiency of the boiler and the power requirements of the equipment used in the above mentioned installations were calculated. These values and also the net efficiency of the analyzed plant were determined as a function of the oxygen recovery rate in the membrane (R). The net efficiency is lower by 7.26 percentage points in comparison with the reference system. The basic method to reduce the loss of net efficiency is to introduce an integrated system, both with a boiler and an ASU installation lignite drying system. This allowed for the reduction of the loss of net efficiency of up to 3.9 percentage points for the lignite dried to w = 20% and 3.3 percentage points at w = 10%. Increase in the intensity of the drying of the lignite not only causes an increase in the maximum system efficiency but also reduces the required membrane surface. A further reduction in the loss of efficiency is sought in the thermal integration of all installations with a steam turbine. This procedure which may improve efficiency by approximately 0.4 percentage point is intended to allow the closure of extractions in the steam turbine and an increase in turbine power.

1. Introduction

Power generation based on fossil fuels is a major source of anthropogenic carbon dioxide emitted into the atmosphere. Emission limitations imposed on electricity producers in the European Union by both the EU institutions and national lawmakers compel them to search for technologies that allow for the radical reduction of the amount of pollutants emitted into the atmosphere. In recent years, mainly due to the adoption of the so-called 'climate package', special attention is given to reducing the emissions of greenhouse gases, mainly carbon dioxide. Approved by the European Union, the climate package assumes that the emission of CO_2 into the atmosphere without the payment of penalties will be possible after the purchase of emission allowances on the free market. This concerns particular companies in which the production of electricity is based on carbon. With currently available technology, a lignite-fed supercritical power unit that generates a power of 600 MWe has CO_2 emissions of approximately 857 kg CO_2/MWh. The purchase cost of the emission allowances, which is imposed on energy producers, is transferred to the price of the product, i.e., the electricity supplied to the customers. To avoid a drastic increase in electricity prices, it appears necessary to minimize carbon dioxide emissions. Technologies under consideration to reduce CO_2 emissions can be divided into three main groups [1]:

- Pre-combustion (CO_2/H_2 separation).
- Post-combustion (N_2/CO_2 separation).
- Oxy-combustion (O_2/N_2 separation).

In the pre-combustion method, fuel is gasified in a stream of air or oxygen in order to obtain a gas consisting mainly of CO and H_2; then, the mixture is separated, usually by the use of RECTISOL or SELEXOL technology [1,2]. The pre-combustion method applies to both natural gas (Natural Gas Combined Cycle – NGCC) and carbon (Integrated Gasification Combined Cycle – IGCC). The application of this method reduces the overall efficiency of the system by approximately 11 percentage points [2].

The post-combustion method is based on the capture of carbon dioxide from the flue gas stream produced by the combustion of fuel in air. Flue gas mainly consists of nitrogen and carbon dioxide, so post-combustion technology is focused on the separation of these two components. For this method, two technologies are currently considered: chemical absorption with the use of

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Nomenclature

Abbreviations

ASU	air separation unit
CCS	carbon capture and storage
CFB	circulating fluidized bed
ESP	electrostatic precipitator
FWH	feed water heater
HTM	high temperature membrane
IGCC	integrated gasification combined cycle
NGCC	natural gas combined cycle
LHV	lower heating value
pp	percentage point

Symbols

A	surface, m^2
c_p	specific heat at constant pressure, $J\ kg^{-1}\ K^{-1}$
C	membrane permeation coefficient, $mol\ s^{-1}\ m^{-2}$
d	thickness, m
h	specific enthalpy, $J\ kg^{-1}$
J_{O2}	oxygen permeation rate, $dm^3\ s^{-1}\ m^{-2}$
L	length, m
$\dot{m}$	mass flow, $kg\ s^{-1}$
$\dot{n}$	molar flow, $mol\ s^{-1}$
N	power, W
$\dot{Q}$	heat flow, W
r	vaporization heat, $J\ kg^{-1}$
R	oxygen recovery rate, –
T	temperature, K
w	moisture content, –
W_d	lower heating value, $J\ kg^{-1}$
X_{O2}	oxygen molar fraction, –

Greek symbols

β	compression rate, –
δ	auxiliaries rate, –
η	efficiency, –

Indices

a	air
ASU	air separation unit
aux	auxiliaries
CCS	carbon capture installation
CFB	circulating fluidized bed boiler
CP	condensate pump
el	electric
f	fuel
F	feed
FWP	feed water pump
g	gross
net	net
o	reference
P	permeate
s	steam
ST	steam turbine
TG	gas turbine
th	thermal
VP	vacuum pump

monoethanolamine (MEA) and membrane separation. In the case of chemical separation, the carbon energy consumption of the dioxide capture process is approximately 200 kWh/tonne of CO_2 [2,3]. In the case of the application of technology using membrane capture, depending on the selected configuration the energy consumption of the CO_2 separation process, the energy consumption ranges from 210 kWh/tonne of CO_2 (single membrane) to 300 kWh/tonne of CO_2 (cascade) [2]. Taking into account the energy consumption of the process of compressing and liquefying a stream of carbon dioxide (approximately 100 kWh/tonne of CO_2 [2]), use of post-combustion methods reduces the overall efficiency of the system by approximately 10–13 percentage points. In the case of membrane technology, relatively high investment costs are important. For the block with a gross power generation of 600 MWe, it would be necessary to use membranes with an area of more than 3.0 million m^2, which at a price of approximately $50/$m^2$ of the membrane generates considerable costs [4]. In the future, use of the membrane with a selectivity ratio of 200 and heat recovery from the separation and compression process can reduce the mentioned loss of efficiency to 8 pp [5,6].

Both of the abovementioned methods cause a significant decrease in the net efficiency of electricity production, and thus oxy-combustion, a third way to reduce CO_2 emissions, is gathering interest. Depending on the technology for the production of oxygen, this method can reduce the efficiency loss to 5.3 [7] – 8.5 pp [1]. This method assumes combustion of the fuel in an atmosphere with an increased content of oxygen together with the elimination of nitrogen from the combustion process [8]. The elimination of nitrogen is possible through the use of the technology of oxygen separation from air and mixing oxygen with a stream of recirculated exhaust gas. As a result, assuming a relatively high purity of the technical oxygen, the combustion product is a flue gas stream which contains more than 90% carbon dioxide [9,10]. This will allow for the reduction or almost complete avoidance of the cost of CO_2 capture [11,12]. The disadvantage of this method is the need to provide a suitable stream of pure oxygen for combustion. Oxygen generation technologies can be divided into cryogenic separation and membrane separation.

The cryogenic separation of oxygen from air uses multiple columns (typically two) in a cryogenic distillation process to obtain high purity oxygen. This process is characterized by high energy consumption: 160 kWh/tonne of O_2 [11,13] to 200 kWh/tonne of O_2 [14] (in extreme cases, it is up to 240 kWh/tonne of O_2 [1]). The production of sufficient oxygen with a purity greater than 95% is attributable to the loss of power plant efficiency by 8–10 pp.

The second technology of oxygen production is separation based on high temperature ceramic membranes (HTM). These membranes are characterized by the permeability of oxygen at operating temperatures of 600–950 °C [15]. In terms of operation, high temperature membranes can be divided into two types: 3-end and 4-end [16,17].

In the case of 4-end type membranes, oxygen transported through the membrane surface goes to the recirculated flue gas flow (so called sweep). The major disadvantage of this solution is the need to recycle gas to the oxygen separation process, which requires approximately 70% of the flue gas volumetric flow at a temperature of 700 °C [18]. Removing such an amount of flue gas causes a serious disturbance in the temperature profile in the convection pass of the boiler and requires major interference with the construction of the boiler itself. Another essential drawback of this solution is that the membrane surface is in contact with flue gas contaminated by SO_2, NO_x and dust. The consequence will be a gradual deterioration of the properties of the membrane with the passage of time and, consequently, a lowered lifetime. The