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Efficiency analysis of a hard-coal-fired supercritical power plant with a four-end high-temperature membrane for air separation

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ABSTRACT

The supercritical power plant analyzed in this paper consists of the following elements: a steam turbine, a hard-coal-fired oxy-type pulverized fuel boiler, an air separation unit with a four-end-type high-temperature membrane and a carbon dioxide capture unit. The electrical power of the steam turbine is 600 MW, the live steam thermodynamic parameters are 650°C/30 MPa, and the reheated steam parameters are 670°C/6 MPa. First of all the net efficiency was calculated as functions of the oxygen recovery rate. The net efficiency was lower than the reference efficiency by 9–10.5 pp, and a series of actions were thus proposed to reduce the loss of net efficiency. A change in the boiler structure produced an increase in the boiler efficiency of 2.5–2.74 pp. The range of the optimal air compressor pressure ratio (19–23) due to the net efficiency was also determined. The integration of all installations with the steam turbine produced an increase in the gross electric power by up to 50.5 MW. This operation enabled the replacement of the steam regenerative heat exchangers with gas–water heat exchangers. As a result of these alterations, the net efficiency of the analyzed power plant was improved to 5.5 pp less than the reference efficiency.

1. Introduction

The reduction of anthropogenic emissions of greenhouse gases presents a major challenge for power engineering in the 21st century. The emission of these gases is associated with fossil fuel combustion and has a significant impact on global climate change. However, the share of fossil fuels in energy production within the next 20–30 years will remain significant. Hard coal is one of the most important fossil fuels due to its large and evenly distributed resources throughout the world and its relatively stable price. For these reasons, despite the increase in energy production from renewable energy sources, hard coal will remain as the main fuel for power plants. Currently, approximately 39% of global electricity is produced from this fuel, and estimates predict that approximately 11,600 TWh of electricity will be produced using coal technologies in 2030, equivalent to 194% of the electricity produced in 2000. The share of electricity produced from coal in Poland in 2010 was equal to 93% [1]. The average net efficiency of electricity production in Polish hard-coal power plants is close to 40%, with average emissions of 855 kg CO_2/MWh. Depending on the country's development scenario, the share of coal in electricity production in 2030 is projected in the range of 57–67%. Considering these quantities, studies are needed on the development of structures and construction of new power plants with high efficiency and lower carbon dioxide emissions.

It is well known that application of a CCS installation is associated with a significant decrease in the net energy efficiency of a power plant. High expectations for reduction of energy consumption via the CO_2 capture process are associated with the so-called oxy-combustion technology, in which the flue gas exiting a boiler contains a higher concentration of carbon dioxide. In this technology, hard coal is combusted in a mixture of oxygen and recirculated flue gas. As a result, the flue gas consists mainly of carbon dioxide and steam. After condensation of steam, the concentration of carbon dioxide in the flue gas exceeds 90%. Using this approach, the power consumption of the carbon dioxide capture process is reduced to a value near the lower limit of the range of 110–170 kWh/t_{CO2}. Such results were presented by Darade [2] and by Pipiton and Bolland [3].

The main problems in oxy-combustion technology are the oxygen production and energy consumption of this type of production. In the power plant analyzed in this paper, the oxygen production was approximately 1000 TPD (ton per day). Cryogenic air separation is the only sufficiently developed technology able to produce such amounts of oxygen at a high purity, above 95%. However, this technology is associated with high energy

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Nomenclature

C	membrane factor, mol/(sm^2)
c_p	specific heat at constant pressure, kJ/(kgK)
d	membrane thickness, m
F	Faraday constant, C/mol
h	specific enthalpy, kJ/kg
j	unit mole flow, mol/(sm^2)
LHV	lower heating value, kJ/kg
$\dot{m}$	mass flow rate, kg/s
$\dot{n}$	mole flow rate, kmol/s
N	power, kW
p	pressure, Pa
$\dot{Q}$	heat flux, kW
R	oxygen recovery rate, %
t	temperature, °C
T	temperature, K
β	compressor pressure ratio, –
δ	auxiliary power rate, %
η	efficiency, %
Indices	
AC	air compressor
ASU	air separation unit
AUX	auxiliary
B	boiler
CC	CO_2 processing unit
CDC	carbon dioxide compressor
CDP	carbon dioxide pump
CM	coal mill
CP	condensate pump
e	effective
ECP	extraction condensate pump
el	electric
EP	electrostatic precipitator
f	fuel
F	feed
F1	flue gas fun
F2	recirculated flue gas fun
gross	gross
GT	gas turbine
HTM	high-temperature membrane
i	isentropic
in	at the inlet
m	isentropic
MP	main water pump
net	net
O_2	oxygen
out	at the outlet
P	permeate
RHE	regenerative heat exchanger
s	supplied
ST	steam turbine
Δ	increase

consumption. The standard value of this energy consumption is approximately 240 $\mathrm{kWh/t_{O2}}$. Consequently, the power plant's net energy efficiency is decreased by 8–12 percentage points compared with that of conventional air-combustion power plants [4,5]. The loss of this efficiency can be reduced by optimization of the cryogenic separation process [2,6] or by oxygen pre-enrichment of the air using polymeric membranes prior to the cryogenic separation process [7]. Currently, research is underway on pilot oxy-type boilers with a thermal power of 15 and 30 $\mathrm{MW_{th}}$ [8]. Due to the experience gained from these advances, a demonstration power plant with a gross power of 250 MW will be built in the near future [8], and this power plant will contain an oxy-type boiler and a CCS installation.

A reduction of the energy consumption in the oxygen production process is expected from the introduction of new technologies, and of these technologies, the most important are high-temperature membranes (HTM) [9]. These membranes separate oxygen from the air at a temperature of 700–900 °C and are made from an ionic conductor of oxygen molecules. Therefore, they produce a pure (100%) oxygen product [10]. The ION (ion transport membrane) or OTM (oxygen transport membrane) shortcuts are also used for their respective designations. These membranes operate according to the so-called three-end or four-end concepts. Castillo [11,12] has shown that the use of an HTM in a three-end concept increases the power plant efficiency by 4 percentage points compared with that of a power plant with a cryogenic air separation unit. Stadler and other authors [13] have shown that the use of an HTM for oxygen production contributes to a reduction of energy consumption in the range of 30–100 $\mathrm{kWh/kg_{O2}}$. Stadler et al. [13] also reports that a higher net energy efficiency is in a power plant with a four-end HTM rather than with a three-end HTM. However, Pfaf and Kather [14] compared power plants containing a cryogenic ASU (air separation unit) with a power plant containing an HTM-ASU and did not find any significant differences in their efficiencies.

2. Block diagram of the power plant

The simplified structure of the analyzed power plant is shown in Fig. 1 and contains the following elements.

(a) A 600-MW steam turbine (ST) fed by supercritical live steam with parameters of 650°C/30 MPa and reheated steam with parameters of 670°C/6 MPa.
(b) An air separation unit (ASU) with a four-end HTM used for the production of oxygen.
(c) An oxy-type pulverized fuel boiler powered with hard coal.
(d) An installation for preparation and compression to 150 bar of carbon dioxide (CC) formed in the combustion process.

The net efficiency of the electricity generation depends on the steam turbine electric power (N_{el}), the sum of the auxiliary powers of the power plant (ΣN_{AUX}), the fuel mass flow rate ($\dot{m}_{\mathrm{f}}$) and the fuel lower heating value (LHV). The net efficiency in the analyzed power plant is determined using the following formula:

$$\eta_{\mathrm{el,net}} = \frac{N_{\mathrm{el}} - \Sigma N_{\mathrm{AUX}}}{\dot{m}_{\mathrm{f}} \cdot \mathrm{LHV}} \tag{1}$$

Eq. (1) uses the auxiliary power rate of the power plant (δ) and the thermal boiler efficiency (η_{B}):

$$\delta = \frac{\Sigma N_{\mathrm{AUX}}}{N_{\mathrm{el}}} \tag{2}$$