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Thermodynamic evaluation of supercritical oxy-type power plant with high-temperature three-end membrane for air separation

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Abstract Among the technologies which allow to reduce greenhouse gas emissions, mainly of carbon dioxide, special attention deserves the idea of 'zero-emission' technology based on boilers working in oxy-combustion technology. In the paper a thermodynamic analysis of supercritical power plant fed by lignite was made. Power plant consists of: 600 MW steam power unit with live steam parameters of 650 °C/30 MPa and reheated steam parameters of 670 °C/6 MPa; circulating fluidized bed boiler working in oxy-combustion technology; air separation unit and installation of the carbon dioxide compression. Air separation unit is based on high temperature membrane working in three-end technology. Models of steam cycle, circulation fluidized bed boiler, air separation unit and carbon capture installation were made using commercial software. After integration of these models the net electricity generation efficiency as a function of the degree of oxygen recovery in high temperature membrane was analyzed.

Keywords: Oxy-combustion; Membrane technology; Air separation unit; Thermodynamic evaluation

1 Introduction

In the light of the existing legislation, both domestic (Polish) and European Union, producers of electricity based on fossil fuels were faced with the need

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to reduce carbon dioxide (CO_2) emissions. Introduction of carbon dioxide emission allowances trading system forced search for electricity generation technologies with minimal possible CO_2 emission. Significant emissions of carbon dioxide from power units supplied with coal (both hard coal and lignite) with high prices of emission allowances will result in a significant increase in electricity prices [1]. Taking into account the structure of energy sources in Poland this problem will particularly affect Polish producers of electricity. Each type of technology reducing the carbon dioxide emissions is characterized by a high energy consumption and hence results in a significant loss of electricity production efficiency. The aim of the development of energy production technologies should be limitation of CO_2 emissions with simultaneous reduction in efficiency loss. Currently developed technologies of low emission electric energy production can be divided into three main groups which are shown in Fig. 1.

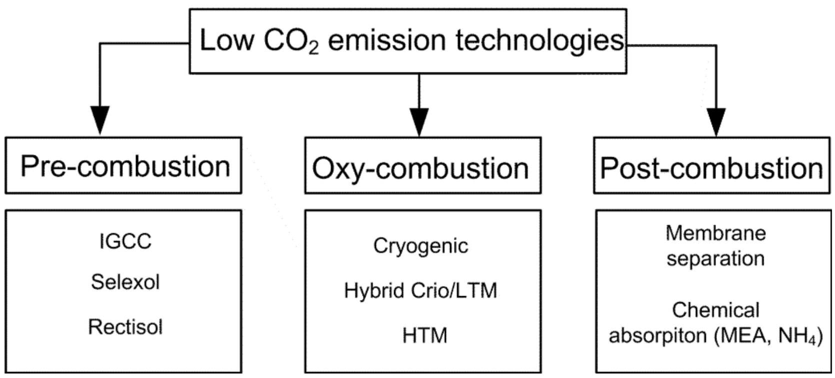

Figure 1: Low CO_2 emission technology groups.

Application of pre-combustion methods (i.e., IGCC – integrated gasification combined cycle) reduces the overall efficiency of the system by approximately 11 pp [2]. In post-combustion technology with the use of the CO_2 separation membranes 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 [3,4]. The last of these groups, oxy-combustion, assumes the elimination of nitrogen from the combustion by separating air on the stream of pure oxygen and a mixture of nitrogen and oxygen resulting in the exhaust gas obtained from the combustion process consisting mainly of carbon dioxide. For separation of air various methods are used. The most common solution for air separation is a relatively high energy consuming cryogenic separation [5–8], therefore, as a part of the searching for alternatives to cryogenic technology the high-temperature membranes (HTM) were decided to be used in this process [9,10].

This article presents thermodynamic evaluation of oxy-type power unit operating in supercritical conditions (live steam parameters: 650 °C/30 MPa, reheated steam parameters: 670 °C/6 MPa) with circulating fluidized bed (CFB) boiler fed with lignite and membrane based air separation unit.

2 Computational model of supercritical oxy-type power unit

For the thermodynamic evaluation a computational model of oxy-type power unit with supercritical CFB boiler and air separation unit based on high-temperature membranes was built. Individual models: CFB boiler, steam cycle consisting of: steam turbine (ST) and generator (G), air separation unit (ASU) and CO_2 drying, flue-gas desulfurization (FGD), and compression carbon capture(CC) installations have been built and integrated in the commercial GateCycle software computer program. Schematic of the integrated oxy-type power unit is shown in Fig. 2 [11].

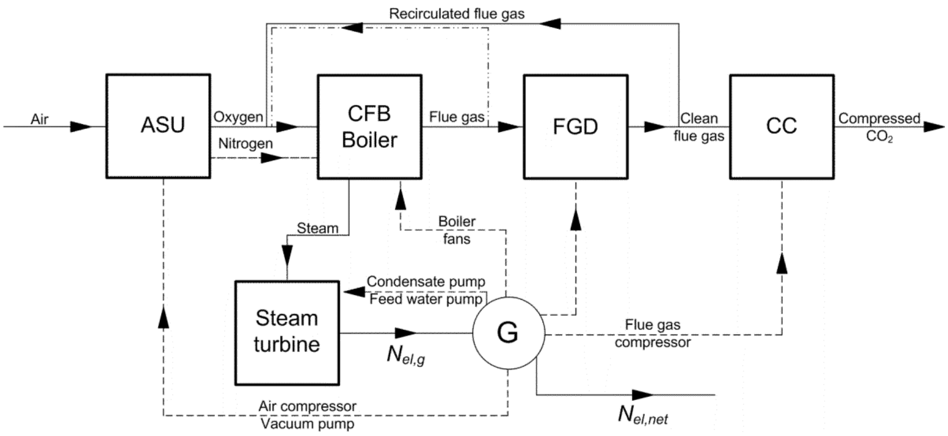

Figure 2: Schematic of the oxy-type power unit [11], $N_{el,g}, N_{el,net}$ are the gross and net electric power, respectively.

At the initial stage of oxy-combustion power plant model calculations it was assumed that the gross electric power, $N_{el,g}$, will be kept at a constant level 600 MW. For this purpose, it was necessary to create a computational model of the steam cycle, which would serve to determine the input streams of steam into the boiler at constant parameters.

Steam cycle consist of:

- three-sectional steam turbine: high-, intermediate- and low-pressure part,
- seven regenerative heat exchangers,
- steam cooler,
- deaerator,
- condensate pump,
- feed water pump driven by electric motor.

Parameters of live steam at the inlet to the high-pressure turbine was assumed at 650 °C/30 MPa, reheated steam parameters at 670 °C/6 MPa and the boiler feed water temperature was set at 310 °C. Other steam cycle assumptions:

– internal efficiency of the turbine sections (in order: high-/intermediate-/low-pressure and the last group low-pressure) – 90/93/86 and 81%,

– internal efficiency of pumps – 85%,

– efficiency of electricity generation in generator – 99%,

– pressure in the condenser – 5 kPa,

– operating pressure in the deaerator – 1.2 MPa.

During the test calculations of steam cycle model, a complete set of results was obtained, of which the most important are shown in Tab. 1.

Table 1: Results of the steam cycle calculations.

Quantities	Unit	Value
Live steam stream	kg/s	412.76
Reheated steam stream	kg/s	348.58
Heat supplied to the steam cycle	GW	1.155

One of the main elements of the power unit operating in the oxy-combustion technology is boiler with circulating fluidized bed fed (CFB) with lignite. To simulate operation of the first pass of the boiler computational model – block consisting of: combustion chamber (AC), evaporator

(EVAP), last stage of superheater (SH II) and last stage of reheater (RH II) was used. In the direction of flue gas flow this block ends with particle separator (cyclone), followed by first stage of superheater (SH I), first stage of reheater (RH I) and economizer (ECO I). Boiler is supplied with Turów-type lignite, where schematic of the CFB boiler integrated with ASU installation and CC installation is shown in Fig. 3. The lignite is composed of: C – 28.60%, S – 0.95%, N – 0.25%, H – 2.20%, O – 8.00%, ash A – 17.50%, moisture W – 42,5%. The fuel of such composition is characterized by a lower heating value equal to 9960 kJ/kg. Most important assumptions for CFB boiler calculations are shown in Tab. 2.

Table 2: Main assumptions for CFB boiler.

Quantities	Unit	Value
Feed water temperature	°C	310
Feed water temperature at the outlet of economizer	°C	340
Steam temperature at the outlet of evaporator	°C	480
Live steam temperature	°C	654.9
Live steam pressure	MPa	31.1
Reheated steam temperature	°C	672.4
Reheated steam pressure	MPa	6.147
Temperature difference at the cold end of economizer	K	55
Oxygen excess ratio	–	1.2
Oxygen content in the oxidizer fed to the boiler	%	30
Temperature difference in the RGH	K	30

In oxy-combustion technology classic oxidant (air) is replaced with oxygen mixed with recirculated flue gas. In our case it is assumed that the oxygen for the combustion process will be supplied from the air separation unit (ASU) based on high-temperature membranes (HTM) technology. Of the two types of HT membranes *three-end* configurations were selected. This configuration is characterized in that there is no sweep stream on the permeate side of the membrane.

In the presented computational model of the air separation unit, the membrane was treated as a 'black box', in which, at the assumed composition of the permeate, the decision variable was the oxygen recovery rate from the air

$$R = \frac{(\dot{n}_{O2})_P}{(\dot{n}_{O2})_F} \ , \tag{1}$$

where the indices P and F denote permeate and feed, respectively.

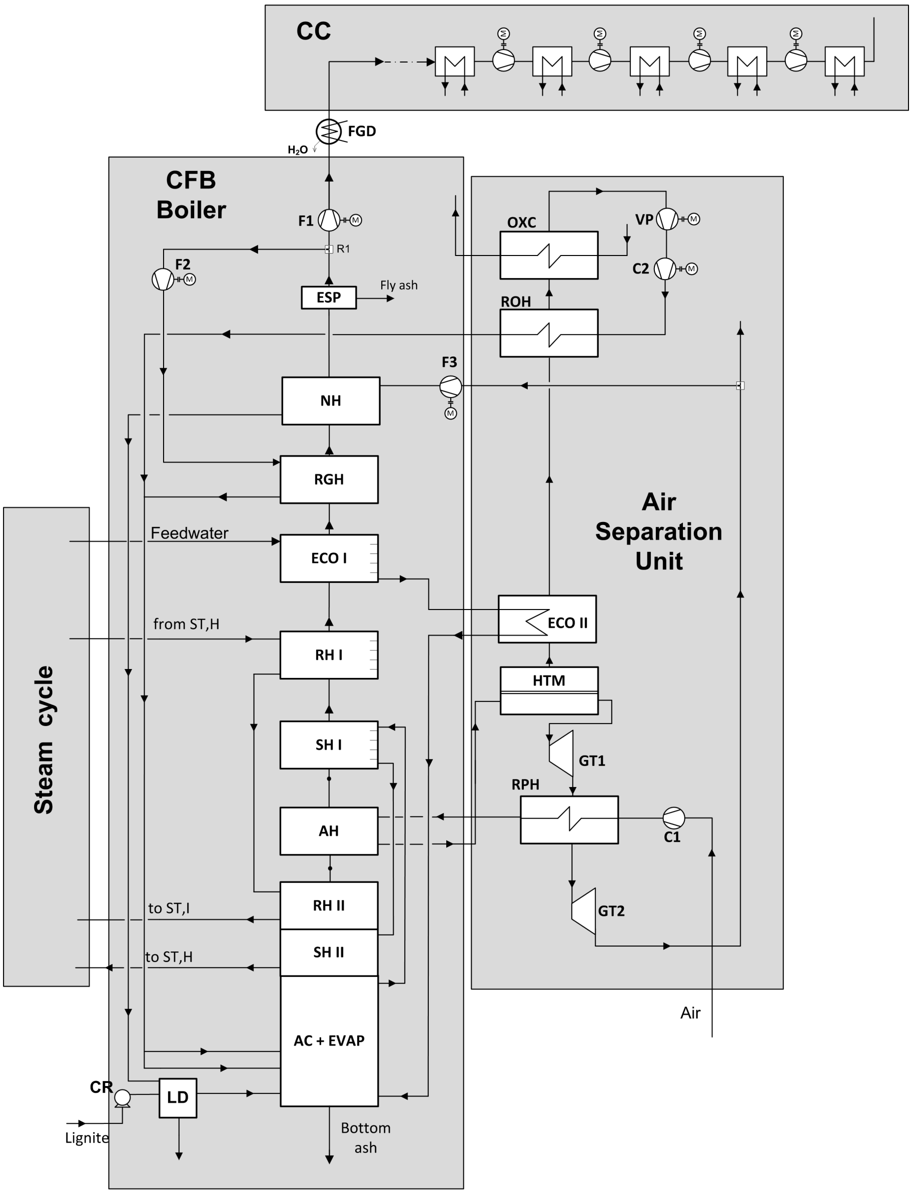

Figure 3: Schematic of CFB boiler integrated with ASU installation and CC installation: LD – lignite dryer; OXC – oxygen cooler; ROH – regenerative oxygen heater; RPH – regenerative air preheater; AH – air heater; RGH – recirculated gas heater.

The air fed to the membrane separation process (feed) is compressed to a pressure of 1.4 MPa, and then heated to the operating temperature equal to 850 °C. The membrane is made of perovskite, through which in a temperature within the range of 700–1000 °C only oxygen ions are transported [12]. Therefore, on the permeate side, where there is a vacuum of 42.5 kPa, 100% pure technical oxygen is obtained. Oxygen stream is cooled to a temperature of 20 °C at the inlet to vacuum pump. The retentate stream which is characterized by a high pressure (similar to the feed stream pressure), consisting mainly of nitrogen is expanded, and then directed to the fuel drying installation. Schematic of the air separation unit integrated with CFB boiler is shown in Fig. 2.

After integration of CFB boiler model with the ASU model the following changes in the structure of the boiler were made:

- air preheater is placed between the particle separator and the first stage of the live steam superheater,
- economizer has been divided into two sections: the first section is heated by flue gas stream, while the second section is heated by permeate (oxygen) stream from the membrane separation process.

Part of flue gas, which is not recirculated, is dried and then directed to the CO_2 compression installation. Installation of carbon dioxide compression consists of four compressor stages which are placed between flue gas coolers. In each cooler the stream of carbon dioxide is cooled to a temperature of 40 °C. It was assumed that the CO_2 stream is compressed to a pressure of 15 MPa, and pressure ratios in all compressor stages are equal. Schematic of carbon dioxide compression installation is shown in Fig. 2.

3 Thermodynamic evaluation methodology

The main method of thermodynamic evaluation of the power unit is to determine the net efficiency of electricity production. The net system efficiency in every power unit may be presented as

$$\eta_{el,net} = \frac{N_{el,g} - N_{el,aux}}{m_f LHV} , \tag{2}$$

where: $N_{el,g}$ – gross electric power, MW; $N_{el,aux}$, plant auxiliaries power, MW; m_f, fuel stream, kg/s; LHV, lower heating value, MJ/kg. After transformation, the formula takes the form:

$$\eta_{el,net} = \frac{N_{el,g}}{m_f LHV}\left(1 - \frac{N_{el,aux}}{N_{el,g}}\right) , \tag{3}$$

where $\frac{N_{el,aux}}{N_{el,g}}$ is called the auxiliaries ratio δ_{aux}. Using equation for thermal efficiency of the boiler

$$\eta_{th} = \frac{Q_d}{m_f LHV} , \tag{4}$$

where Q_d is the heat supplied to the steam cycle, MW we obtain a formula for the net efficiency of the electricity production:

$$\eta_{el,net} = \frac{N_{el,g}}{Q_d}\eta_{th}\left(1 - \delta_{aux}\right) . \tag{5}$$

Auxiliaries ratio of the power unit is defined as a sum of auxiliary power of the individual elements of the power unit:

$$\delta_{aux} = \delta_{ASU} + \delta_{CC} + \delta_{ST} + \delta_{CFB} . \tag{6}$$

Flue gas dryer installation (FGD) auxiliary power ratio, due to the low energy consumption of this installation, has been omitted.
Steam cycle auxiliary power ratio is defined as

$$\delta_{ST} = \frac{N_{el,CP} + N_{el,FWP}}{N_{el,g}} , \tag{7}$$

where CP is the condensate pump, and FWP is the feed water pump. CFB boiler auxiliary rate was calculated using the relation

$$\delta_{CFB} = \frac{N_{el,F1} + N_{el,F2} + N_{el,F3} + N_{el,CR} + N_{el,ESP}}{N_{el.g}} , \tag{8}$$

where the particular symbols denote: F1 – exhaust fan, F2 – recirculated flue gas fan, F3 – nitrogen fan, CR – lignite crushers, ESP – electrostatic precipitator. The CC installation auxiliary rate is defined as

$$\delta_{CC} = \frac{\sum_{i=1}^{i=4} (N_{el,CO_2})_i}{N_{el,g}} . \tag{9}$$

The ASU installation auxiliary rate was set using the formula

$$\delta_{ASU} = \frac{N_{el,C1} + N_{el,VP} - N_{el,GT1} - N_{el,GT2}}{N_{el,g}} , \tag{10}$$

where: $C1$ – air compressor, VP – vacuum pump, $GT1, GT2$ – nitrogen expanders.

4 Results

The thermodynamic evaluation was performed for two variants of the extent of drying of fuel, which is defined as the water content in the dried fuel. During the analysis, the fuel was drained to 10 and 20% moisture content in the dried fuel.

First stage of the analysis was to determine CFB boiler thermal efficiency as a function of oxygen recovery rate. Results of this analysis are shown in Fig. 4.

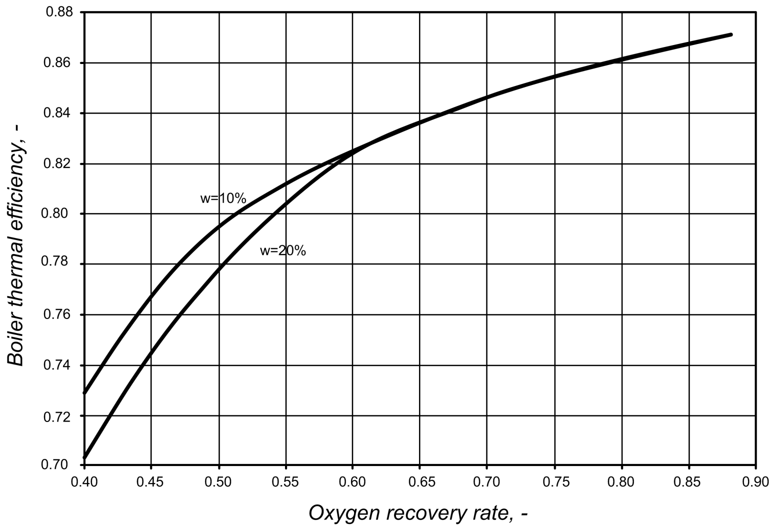

Figure 4: Boiler thermal efficiency as a function of oxygen recovery rate, w – moisture content in dried fuel.

In both scenarios the boiler thermal efficiency increases with increasing the oxygen recovery rate. This happens because with increasing oxygen recovery rate decreases the air flow supplied to the ASU installation, and hence the thermal load of the boiler. For a more favorable variant (drying down to 10% moisture content in the fuel) thermal efficiency of the boiler increases from the value of 72.8% for oxygen recovery rate $R = 0.4$ to the value of 87.2% for $R = 0.885$.

The next stage of the analysis was to determine the total power unit auxiliary rate as a function of the oxygen recovery rate in the membrane. Results of this analysis are shown in Fig. 5.

It can be observed that for both variants of fuel drying summarized

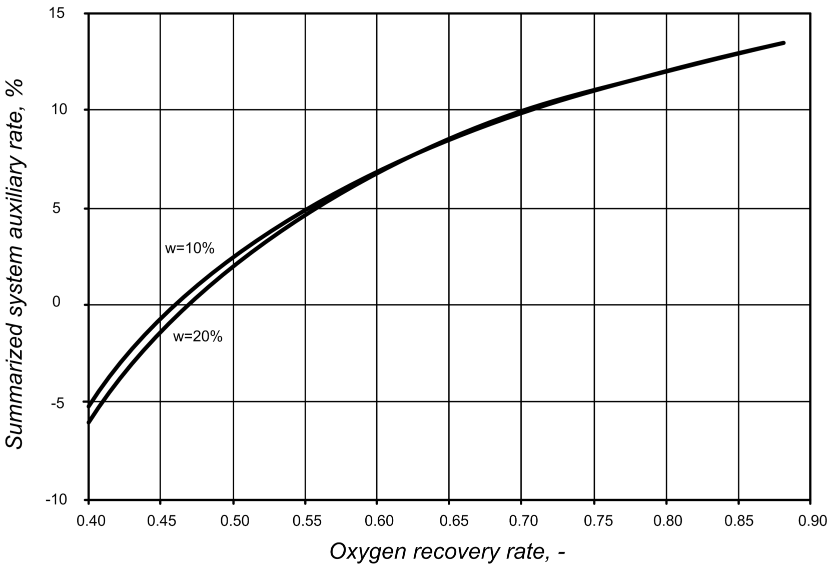

Figure 5: Summarized system auxiliary rate as a function of oxygen recovery rate, w – moisture content in dried fuel.

auxiliary rate increases with the oxygen recovery rate in the membrane, and both characteristics are similar. For the lowest values of the oxygen recovery rate summarized system auxiliary rate is negative. This occurs because in the ASU installation during the expansion of nitrogen more energy is obtained than is needed to drive the air compressor and vacuum pump. For drying down to 10% moisture content in the fuel summarized system auxiliary rate increases from the value of -5% for $R = 0.4$ to the value of 13.8% for $R = 0.885$.

After determining the summarized system auxiliary rate it was possible to determine the characteristics of changes in the net efficiency of electricity production as a function of the oxygen recovery rate in the membrane. Results of this analysis are shown in Fig. 6. As can be seen for each variant of fuel drying an extreme of the net efficiency of electricity production was obtained. In the case of drying down to a moisture content of 20% maximum net efficiency of 39.88% was obtained for oxygen recovery rate equal to 0.61. And for fuel drying down to a moisture content of 10% the net system efficiency is equal to 40.34% for $R = 0.48$.

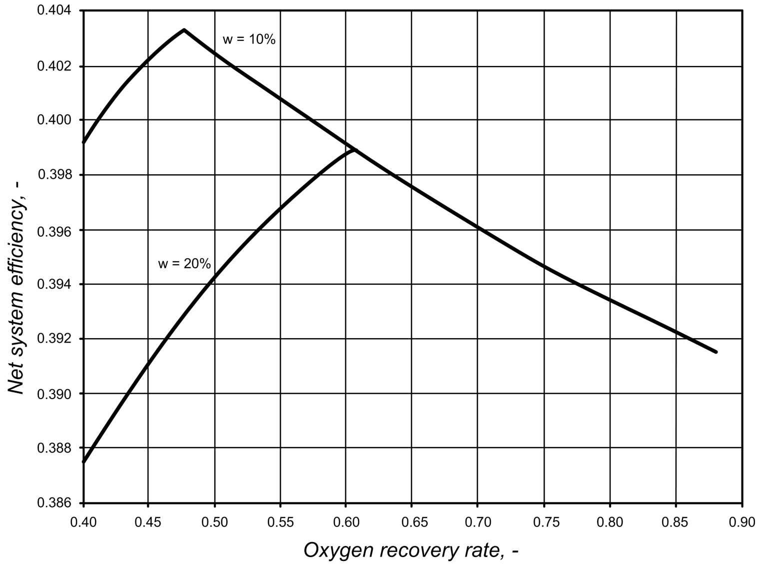

Figure 6: Net efficiency of electricity production as a function of oxygen recovery rate, w – moisture content in dried fuel.

5 Summary

In the paper was performed a thermodynamic evaluation of power unit operating in oxy-combustion technology consisting of four elements, namely the CFB boiler fed with lignite, steam cycle with live steam parameters of 650 °C/30 MPa and reheated steam parameters of 670 °C/6 MPa, pressure in condenser 5 kPa; air separation unit based on high-temperature membrane technology and installation of CO_2 compression.

During the analysis the influence of changes in oxygen recovery rate in the high-temperature membrane on the basic characteristics of the power unit: boiler thermal efficiency, total system auxiliary rate and net system efficiency were investigated. The analysis was performed for two values, namely 10 and 20% of moisture content in the fuel supplied to the combustion chamber. The highest net efficiency of electricity production equal to 40.34% was obtained in the case of the drying of fuel to a moisture content of 10% and the oxygen recovery rate $R = 0.48$. For the second variant of the fuel drying maximum efficiency was lower – equal to 39.88% and was obtained for oxygen recovery rate equal to 0.61.

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