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Analysis of the thermodynamic and economic efficiency of a supercritical power unit with a lignite-fed CFB boiler and an air separation unit based on high-temperature membrane technology

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Abstract

This paper presents a thermodynamic and economic analysis of the supercritical power unit with OXY type circulating fluidized bed boiler fed with lignite and with an air separation unit based on a three-end type high-temperature membrane. The fluidized bed boiler model is integrated with a fuel drying installation, a flue gas dehumidifier and a flue gas stream compression unit for further transportation. Models of the CFB boiler with the fuel drying installation, the air separation unit (ASU) and the flue gas compression installation (CCS) were built using the GateCycle^{TM} software. For the fuel drying process an expanded nitrogen and oxygen mixture stream from the air separation unit was used. Thermodynamic analysis of the power unit assumed examination of certain characteristics of the power unit as a function of the oxygen recovery rate in the high-temperature membrane and selection of the appropriate calculation point for further economic analysis. As part of the economic analysis for a selected operation point of the power unit, the estimated capital expenditures and break-even price of electricity were determined on the assumption that the net present value of investment (NPV) is equal to zero.

Keywords: oxy-combustion, high-temperature membranes, thermodynamic analysis, economic analysis

1. Introduction

Producers of electricity based on fossil fuels are faced with the need to reduce carbon dioxide emissions due to regulations at the domestic and European Union level. Lack of progress in this direction will result in a sharp increase in the cost of electricity associated with the need to purchase allowances to emit carbon dioxide. Currently under consideration are a number of solutions to reduce CO_2 emissions, which can be classified under the following groups:

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

The last of these groups, oxy-combustion, involves the elimination of nitrogen from combustion by separating air into a 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. Various methods are used to separate air. The most common solution for air separation is relatively energy consuming cryogenic

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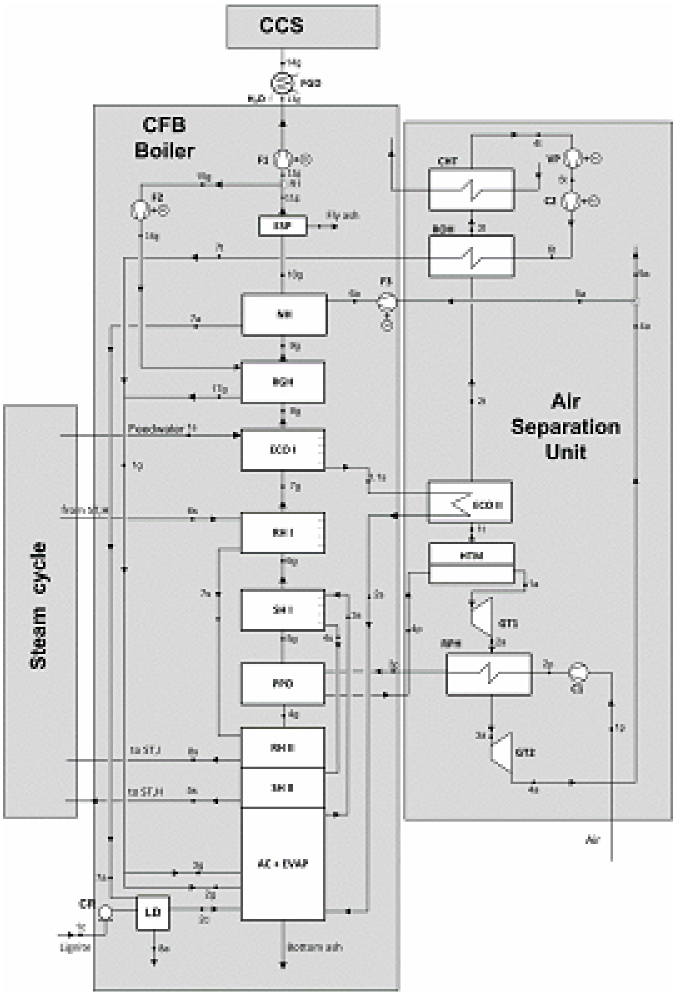

Figure 1: Scheme of the OXY-type CFB boiler integrated with ASU installation.

separation, therefore, as part of the search for alternatives to cryogenic technology, high-temperature membranes (HT) were chosen for use in this process. Reduction of CO_2 emission in OXY-type power systems and the resulting reduction in emission allowance purchases cuts the cost of electricity production [7], but it is not without its drawbacks. The most severe of these drawbacks is higher investment costs than for conventional power systems [8].

2. Description of the investigated system

The model of the supercritical power unit with circulating fluidized bed boiler operating with oxy-combustion technology was built using the GateCycle™ computer program and in-house codes. The scheme of the constructed model is shown in Fig. 1 [6].

At the stage of adopting assumptions for construction it was decided to use the fluidized bed boiler block provided by the GateCycle™ program, consisting of: furnace chamber (AC), evaporator (EVAP) and last sections of the live steam superheater (SH II) and reheated steam superheater (RH II).

In the direction of the flue gas flow this power unit ends with a particle separator (cyclone). After the cyclone there is a gas/gas type heat exchanger (PPO), in which air from the air separation unit (ASU) is heated to the temperature of 850°C. Subsequently, the following exchangers were installed: live steam superheater (SH I), reheated steam superheater (RH I), economizer (ECO I), recirculated exhaust gas heater (RGH) and nitrogen heater (NH). The last devices in the direction of flue gas flow are: electrostatic precipitator (ESP), flue gas fan (F1) and the flue gas dryer (FGD).

In the present model a three-end type high temperature membrane was treated as a black box, where at a given composition of the permeate (in this case 100% oxygen) the recovery ratio of oxygen, defined as the amount of oxygen permeating through the membrane surface to the amount of oxygen supplied to the membrane system with the air, was a decision variable. Heat losses were not included, so each of the streams within the membrane has a temperature of 850°C [1, 3]. The pressure losses within the same membrane were not assumed.

3. Calculation methodology

Net efficiency of electricity generation in every classic power system can be represented as a ratio of the power received at the generator terminals less the auxiliary power and the chemical energy of the supplied fuel:

$$\eta_{el,net} = \frac{N_{el,g} - N_{el,pw}}{m_p \cdot W_d} \qquad (1)$$

In the case based on oxy-combustion technology, after taking into account all the system auxiliaries, the net efficiency of electricity production can be written as [5]:

$$\eta_{el,net} = \frac{N_{el,g}}{Q_d} \cdot \eta_{th} \cdot (1 - \delta_{ASU} - \delta_{CCS} - \delta_{ST} - \delta_{CFB}) \qquad (2)$$

The auxiliary rate is defined as the sum of the electrical power needed to power the devices within a system component minus the power generated by the element to the gross electrical output of the system.

Thermal efficiency of the boiler can be determined directly from the formula:

$$\eta_{th} = \frac{\dot{m}_{5s} \cdot (h_{5s} - h_{1s}) + \dot{m}_{8s} \cdot (h_{8sl} - h_{6s})}{\dot{m}_{1c} \cdot W_{d\_1c}} \quad (3)$$

For the next stage of the analysis, one of the operating points for the oxygen recovery rate in the membrane equal to 0.67 was selected.

The second stage of the study was an economic analysis of the system based on determination of the break-even price of electricity, calculated on the assumption that the net present value of the investment (NPV) is equal to zero [8]. It was assumed that the NPV calculation algorithm is determined iteratively by changing the electricity sale price. NPV is a function of the annual net cash flows CF_t, designated for subsequent years of the power unit operation t and the discount rate r. This value can be determined by the formula:

$$NPV = \sum_{t=0}^{t=N} \frac{CF_t}{(1+r)^t} \quad (4)$$

where: $t = 0$—the year when construction starts; $t = N$—assumed last year of the power unit operation; r—discount rate.

To determine the break-even price of electricity (at $NPV = 0$) for the power unit under study, the following relationship was used:

$$c_{el}^{gr} = \frac{\sum_{t=0}^{t=N} \frac{[J_{BE}+(K_{op}+P_d+K_{obr})-K_A-L]_t}{(1+r)^t}}{\sum_{t=1}^{t=N} \frac{E_{el,netto}}{(1+r)^t}} \quad (5)$$

where: J_{BE}—investment costs; K_{op}—operating costs; P_d—income tax; K_A—amortization costs; L—liquidation value for the last year of power unit operation.

The operating costs in the above formula were determined from the dependence:

$$K_{op} = K_o + K_r + K_u + K_A + K_{pal} + K_e + K_{ps} \quad (6)$$

where: K_o—cost of service, K_r—maintenance costs, K_u—insurance costs, K_{pal}—fuel costs, K_e—operating costs, K_{ps}—costs of other materials.

4. Assumptions for the thermodynamic analysis

At the stage of adopting assumptions for the calculation it was assumed that the gross electric power produced by the generator in steam cycle will be maintained at a constant level of 600 MW.

In order to meet this assumption, it was necessary to maintain at a constant level the heat supplied to the steam cycle with both live and reheated steam streams, which was ultimately set at 1,182 MW. During preliminary analysis, streams of both live steam and reheated steam were determined, and they were respectively: m_{5s}= 431.02 kg/s and m_{8s}= 364.82 kg/s.

The boiler is fed with lignite (point 1c in Fig. 1) composed of: c =28.60%, s =0.95%, n =0.25%, h =2.20%, o =8.00%, ash =17.50%, $moisture$ =42.5%. The most important inputs adopted for the calculations for the CFB boiler are shown in Table 1 [2].

Table 1: Assumptions for the CFB boiler calculations

Parameter	Value
Lower heating value of fuel (Dulong), kJ/kg	9,960
Feed water stream, kg/s	431
Feed water temperature, °C	297
Feed water temperature at the outlet of ECO II, °C	340
Steam temperature at the outlet of evaporator, °C	480
Temperature difference at the cold end of ECO I, °C	55
Oxygen excess ration	1.2
Oxygen content in the oxidizer fed to the boiler, %	30
Temperature difference in the NH, °C	30
Temperature difference in the RGH, °C	30
Ambient pressure, kPa	101
Ambient temperature, °C	15

The lignite dryer model was built on the principle of a heat exchanger, in which the fuel stream is dried by the drying medium (a mixture of nitrogen and oxygen derived from the ASU installation). The drying medium is preheated in a heat exchanger (NH) and placed in the path of flue gas within the CFB boiler. Selected assumptions for the lignite drying process are shown in Table 2 [4].

Table 2: Assumptions for the CFB boiler calculations

Paremeter	Value
Lignite temperature at the inlet to the dryer, °C	15
Drying medium temperature, °C	130
Temperature difference in the dryer, °C	20
Temperature difference in the nitrogen heater (NH), °C	30
Drying medium pressure at the outlet of F3, kPa	108

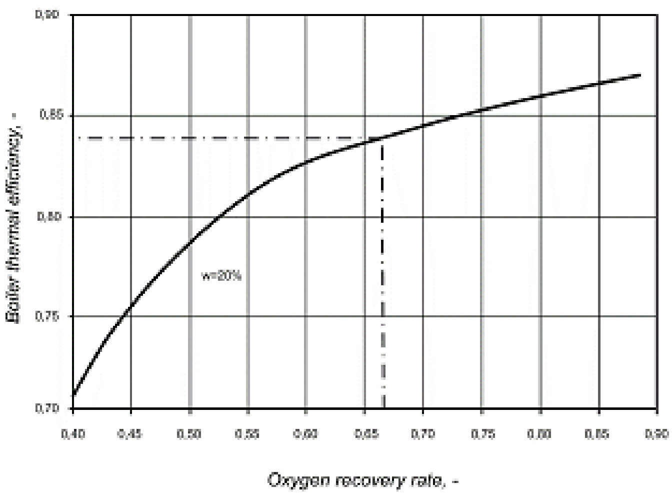

Figure 2: Boiler thermal efficiency as a function of oxygen recovery rate

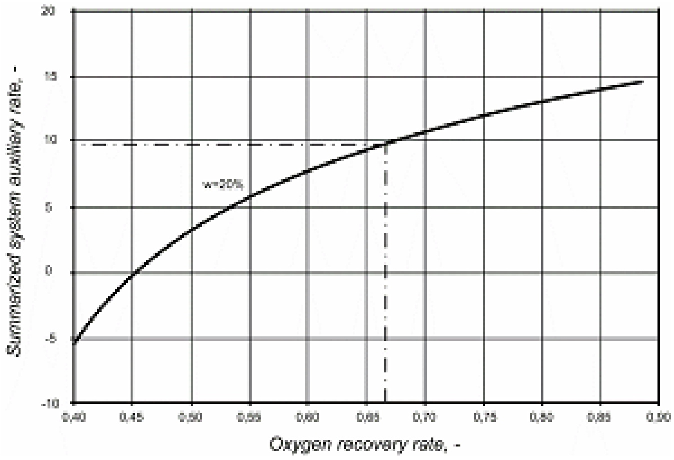

Figure 3: Summarized system auxiliary rate as a function of the oxygen recovery rate in the membrane

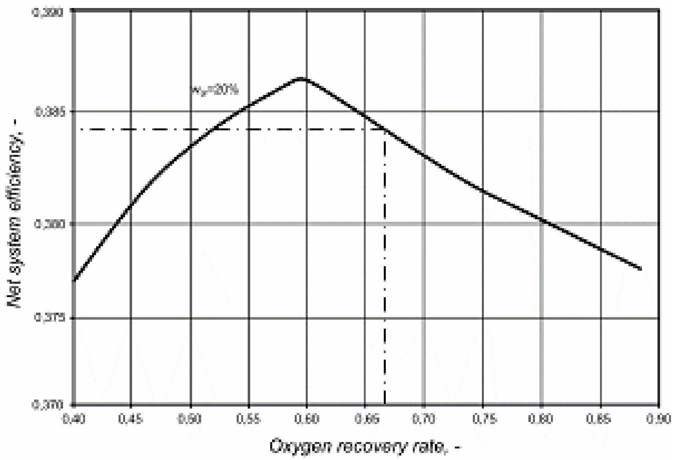

Figure 4: Net system efficiency as a function of oxygen recovery rate

5. Results of the thermodynamic analysis

Fig. 2 shows the results of calculation of the thermal efficiency of the boiler (dependence 1) as a function of the oxygen recovery rate in the membrane. Oxygen recovery rate was varied from 0.4 to 0.886. The study was conducted on the assumption that, in the fuel drying installation, lignite is dried to 20% moisture content.

At the operating point selected for further economic analysis, boiler thermal efficiency was 84.2%, which translates into a fuel flow fed to the boiler of m_{1c}= 141.2 kg/s.

The summarized system auxiliary rate was a significant value at both the thermodynamic analysis (determination of the net efficiency of the system) and the economic analysis stage (determination of the amount of electricity for sale). Fig. 3 shows the characteristics of the summarized system auxiliary rate with a selected operating point chosen for further economic analysis.

At the operating point chosen for further analysis the summarized system auxiliary rate was 9.2%.

The final stage of the thermodynamic analysis was to determine the net efficiency of electricity production in the system under study as a function of the oxygen recovery rate in the high temperature membrane. The result of this analysis are shown in Fig. 4. As can be seen, the characteristic of net efficiency refracts at the operating point for the oxygen recovery rate equal to 0.6. This is because limit moisture content was reached and therefore for lower values of the oxygen recovery rate the calorific value of dry fuel remains unchanged. At the operating point cho-

Table 3: Main assumptions for economic analysis

Paramerer	Value
Gross electric power, MW	600
Operating time, h/a	8,000
Investment costs, PLN/kW	8,390
Construction time, years	5
Distribution of investment costs for each year of construction, %	10/30/25/ /20/15
Share of own funds in investment financing, %	20
Share of commercial loan in investment financing, %	80
Loan interest rate, %	6
Loan repayment time, years	10
Discount rate, %	6.2
Estimated installation operating time, years	20
Average rate of amortization, %	5
Income tax, %	19
Fuel price, PLN/Mg	95.00
Employment, person/MW	0.4
Average salary, PLN/person/ /month	4,600
Salvage value referred to the investment costs, %	20

sen for further economic analysis the net efficiency of the system is 38.4%.

6. Assumptions for the economic analysis

The second stage of the study was to analyze the economic viability of the system under study at the assumed operating point (for oxygen recovery rate in the membrane of 0.67). Since the initial model, for thermodynamic analysis, did not take into account the efficiency of carbon dioxide sequestration, the economic calculation assumed that 8% of the CO_2 produced by the installation is emitted into the atmosphere. The most important assumptions for the economic analysis are shown in Table 3 [8].

7. Economic analysis results

The first step in the economic analysis was to determine the break-even price of electricity ($C_{en,gr}$)

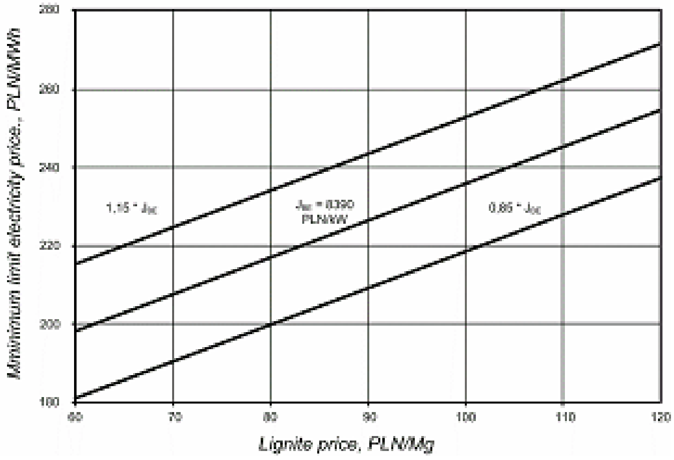

Figure 5: Minimum limit electricity prices as a function of fuel price

for the adopted assumptions in the previous section, which was **PLN 231/MWh**.

During the economic research for the system for the selected operating point, it was assumed that an analysis will be made of the impact on the break-even price of electricity of two selected quantities: the price of lignite and investment costs. The effects of changes in fuel costs were analyzed for three values of investment costs: initial value: PLN 8,390/kW and value 15% higher and 15% lower than the initial. The effects of changes in investment costs were analyzed for three values of fuel prices: initial value: PLN 95/Mg and value 20% higher and 20% lower than the initial.

Fig. 5 shows the effect of changes in lignite prices on the break-even price of electricity. During the studies a change in fuel price in the range 60 to 120 PLN/Mg was analyzed.

The next step was to determine the impact of changes in investment costs (which varied in the range 7,200 to 9,600 PLN/kW) on the break-even price of electricity. The results of this analysis are shown in Fig. 6.

8. Summary

The first stage of the research was a thermodynamic analysis of the system under study. In this stage, subject to analysis was the effect of the change in oxygen recovery rate in the membrane (R) on three basic quantities characterizing the system: boiler

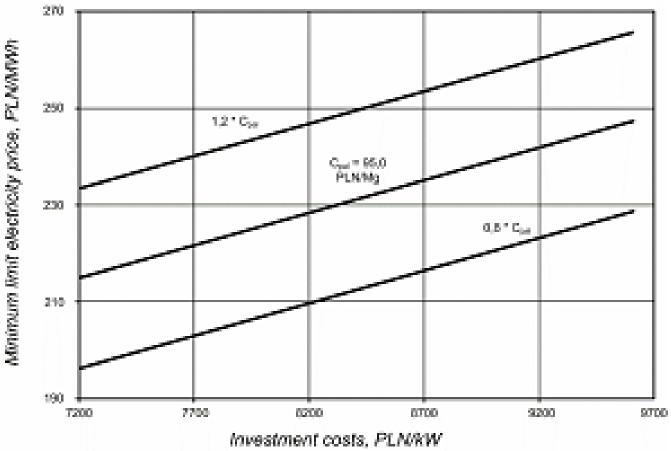

Figure 6: Minimum limit electricity prices as a function of investment costs

thermal efficiency, summarized auxiliary power rate of the system and net efficiency of electricity production. At the operating point selected for further economic analysis (for $R = 0.67$), boiler thermal efficiency was 84.2%, summarized auxiliary power rate of the system was 9.2% and net system efficiency was 38.4%. During the second stage of the study, subject to analysis was the effect of changes in fuel price and investment costs on the break-even price of electricity. The break-even price of electricity increased due to an increase of both fuel prices and investment costs. For the initial variant (investment costs $J_{BE} = 8390\,\text{PLN/kW}$) an increase in fuel prices from 60 to 120 PLN/Mg caused the break-even price of electricity to increase from 199 to 255 PLN/MWh. For an initial fuel price of PLN 95/Mg, an increase of investment costs from 7,200 to 9,600 PLN/kW causes the break-even price of electricity price to increase from 215 to 247.6 PLN/MWh.

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