Coal-fired steam turbine power plant using oxygen-rich air as oxidizer

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Abstract. Mitigation of harmful and greenhouse gases emissions produced by the coal combustion in thermal power plant is a topic goal. Reduction of the nitrogen oxides, sulfur and ash emissions makes remarkable progress but the carbon dioxide emission still meets considerable difficulties mostly caused by the low greenhouse gas content in the flue gas. A prospective solution to this problem may be the fuel combustion in oxygen-enriched air, which increases the flue gas carbon dioxide content. In this technology, the carbon dioxide content in flue gas is higher and this results in its easier capture. This paper presents the thermodynamic analysis results of a steam turbine power production facility that burns coal in the air with high oxygen content. The computer simulation shows that the oxygen content increase from 21 to 95.6% increases the carbon dioxide content in flue gas by a factor of 3.3 and lowers the power consumption for carbon dioxide capture by 11%. On the other side, the power consumption for pure oxygen production reduces the facility’s net efficiency from 28.54 to 21.59%.

1. Introduction

In the last decades, the world community’s attention is attracted by the problem of toxic and greenhouse gases emission. The measures of emission mitigation include carbon taxes [1, 2]. Especially attention is attracted to the emission reduction from the coal firing thermal power plant (TPP). The NOx, sulfur and ash emission by TPP reduction is successful [3], but the carbon dioxide one still meets considerable financial and technical difficulties [4]. For example, an application of the carbon dioxide capture technology in steam turbine unit (STU) TPP reduces its total efficiency by 8–12%.

Three main methods of reducing the carbon dioxide emission by power production steam turbine facilities (figure 1) are the following:

- Pre-combustion capture.
- Post-combustion capture.
- Oxy-fuel combustion capture.

The CO2 capture before fuel combustion in oxygen requires preliminary coal gasification to transform coal into coal-derived gas, which makes the capture process complicated and expensive [5]. The oxy-fuel combustion method allows high carbon dioxide contents in the flue gas of 80–90%, which simplifies its separation and the harmful emission down to reduction down to 1.5% [6]. The technology shortages are the high combustion temperature of 1100 to 1700°C and the need for a large amount of oxygen production in air separation unit, which hurt the practical application and increase the auxiliary
power consumption [7]. Because of that more popular are post-combustion CO₂ capture methods such as chemical absorption, membrane separation, cryogenic separation, and chemical looping combustion.

![CO₂ capture technologies diagram]

**Figure 1. Methods of carbon dioxide capture in TPP.**

Papers [8–10] disclose some performance of the post-combustion capture methods (table 1). The chemical absorption with monoethanolamine (MEA) is an efficient approved method of post-combustion capture widely used in Russia and abroad [11]. This method has higher maturity, CO₂ capture degree, and lower power consumption than other capture methods [12]. Also this absorption method captures the carbon dioxide from the larger flue gas flow (which is typical for STU) than the membrane separation technology. The MEA technology power consumption can be reduced by reduction of the nitrogen content in the flue gas.

| CO₂ capture methods | Chemical absorption | Membrane separation | Cryogenic separation | Chemical looping combustion |
|---------------------|---------------------|---------------------|---------------------|-----------------------------|
| Power consumption, MJ/kgCO₂ | 4–6                 | 0.5–6              | 6–10               | 3.5–5.4                     |
| CO₂ capture degree, % | 90–98              | 80–90             | >95                | ~98–99                      |
| Technology availability | high              | high              | mid                | low                         |

A possible efficient solution to the carbon dioxide capture problem may be the change to STU with the air enriched with oxygen as the combustion oxidizer. This solution increases the flue gas carbon dioxide content so its separation is simplified. This method requires additional power consumption for the production of highly pure oxygen. Therefore, the issue of reduction of the power consumption for carbon dioxide capture in oxy-fuel STU is still being discussed.

This paper describes the influence of oxygen content in combustion air upon the carbon dioxide capture expenses and the STU efficiency.

2. Coal-fired steam turbine power plant using oxygen-rich air as an oxidizer

The study example is the steam turbine coal-firing unit with the oxygen-enriched air as an oxidizer. For the basis version the K-300-240 power unit (figure 2) operating the condensing steam turbine with steam reheat was chosen. This type of turbine works in more than 20 TPP including the high power Kostromskaya, Konakovskaya, and Iriklinskaya. The efficiency of the TPP with carbon dioxide capture is about 33%. Specific features of the discussed unit are the following:

- Air separation unit (ASU).
- Coal firing boiler with capabilities for coal firing in oxygen-enriched air.
- Flue gas recirculation.
- \( \text{CO}_2 \) separation from the flue gas flow by chemical absorption.
- \( \text{CO}_2 \) compression and storage.

The steam turbine unit consists of the condensing turbine K-300-240 LMZ with a steam reheat. The superheated steam enters the power turbine that consists of high, intermediate, and low-pressure turbines. The turbine has eight regenerative bleeding paths directed to three high-pressure feed heaters, a deaerator, and three low-pressure feed heaters. The condensate pump supplies the main part of condensate through the line heater into the low-pressure regeneration line and further into the deaerator. The booster and turbine driven feeding pumps supply the deaerated water to the high-pressure feed heaters and the coal firing steam boiler.

![Figure 2. Schematic chart of the steam turbine unit flow.](image)

The boiler consists of furnace walls, steam superheater, economizer, air heater, and the intermediate superheater line (figure 3). Fuel burns in the environment of ASU produced oxygen. The carbon dioxide is separated from the flue gas flow by the chemical absorption MEA technology. Table 2 summarizes the input data for the STU heat flow computer simulation. An example of fuel is the long-flame Kuznetsk coal that forms about 70% of the Russian coal reserves.

A computer simulation model of the STU operating the oxygen-enriched air and the carbon dioxide compression is developed in the Aspen Plus (figure 4) software environment. The \( \text{CO}_2 \) and \( \text{H}_2\text{O} \) thermo-physical performance are determined with the NIST REFPROP database. The carbon dioxide storage simulation assumes the 10 MPa and 28°C conditions [13].

The boiler combustion process is simulated with the MS Excel code. The simulation assumed the following conventions: constant heat power of the boiler, the adiabatic temperature is equal to the values determined for the air combustion, the adiabatic temperature is reduced by a partly recirculation of flue gas, the exhaust gas temperature is the constant 140°C.

The power consumption for 95.6% pure oxygen production is evaluated by the method presented by paper [14]. The carbon dioxide MEA chemical absorption is simulated by the method in [15]. The carbon dioxide capture degree is assumed at 90%.
Figure 3. Concept heat flow chart of the coal oxygen combustion boiler with CO₂ capture.

Table 2. Input data for the coal firing STU heat flow analysis [16].

| Parameter                                         | Value          |
|---------------------------------------------------|----------------|
| STU power, MW                                     | 300            |
| Steam initial pressure, MPa                       | 23.5           |
| Steam initial temperature, °C                     | 540            |
| Intermediate superheating pressure, MPa           | 3.66           |
| Intermediate superheating temperature, °C         | 540            |
| Condenser pressure, kPa                           | 3.5            |
| Cooling water temperature at the condenser entrance, °C | 15             |
| Deaerator pressure, MPa                           | 0.69           |
| Feed water temperature, °C                        | 270            |
| High pressure-turbine internal specific efficiency | 0.85           |
| Intermediate-pressure turbine internal specific efficiency | 0.91         |
| Low-pressure turbine internal specific efficiency  | 0.82           |
| Number of regenerative heaters, pcs               | 7              |
| Approach in the low / high-pressure heaters, °C   | 5              |
| Heat transition efficiency, %                     | 99             |
| Coal type                                         | long-flame     |
| Kuznetsk coal reserve, billion ton                | 700            |
| Coal operational humidity, %                      | 11.5           |
| Coal ash content, %                               | 15.9           |
| Coal sulphur content, %                           | 0.4            |
| Coal carbon content, %                            | 56.4           |
| Coal hydrogen content, %                          | 4.0            |
| Coal nitrogen content, %                          | 1.9            |
| Coal oxygen content, %                            | 9.9            |
| Low heating value, MJ/kg                          | 21.9           |
| Volatiles, %                                      | 40.5           |
| Grindability index                                | 1.1            |
3. Results

Figure 5 presents the oxygen concentration in oxidizer influence upon the carbon dioxide volume content in the combustion products. When the $O_2$ content grows from 21 to 95.6% the $CO_2$ content in the combustion products grows 3.3 times. A 1% increase of the oxygen content in air results in a mean 2% of $CO_2$ content increase. This is because the increase of oxygen reduces the nitrogen content in flue gas and increases the content of oxidizer in reaction with carbon. This result is confirmed by the investigation results in [17, 18], but mentioned papers only considered pure oxygen for combustion or didn’t consider the use of oxy-fuel combustion with chemical absorption. The carbon dioxide emissions from TPP without CCS were calculated to be 1100 g/kWh, which is on par with 900 g/kWh reported in literature [19].

Figure 6 shows the oxidizer purity influence upon the boiler efficiency in the form of the flue gas flow and the flue gas heat losses. When the $O_2$ content grows from 21 to 95.6% the flue gas flow and the heat losses with flue gas drop down for 68.8 and 53.5% respectively. The reason heat losses with the flue gas do not lower as much as the flue gas flow is because of the constant exhaust temperature and increasing heat capacity of flue gas, which is due to the lower nitrogen content. The results show that the determining factor is the smaller amount of the ballast nitrogen $N_2$ and the smaller total amount of the heated gas.

![Simulation model of an STU operating oxygen-enriched air and CO2 compression and storage.](image)

**Figure 4.** Simulation model of an STU operating oxygen-enriched air and CO2 compression and storage.

![The CO2 content in exhaust gas vs the O2 concentration in oxidizer.](image)

**Figure 5.** The $CO_2$ content in exhaust gas vs the $O_2$ concentration in oxidizer.
Figure 6. Influence of the O₂ content in oxidizer upon the heat losses with flue gas.

Lower heat losses with flue gas cause lower fuel consumption and increase the boiler gross efficiency (figures 7, 8). An increase in the oxygen content in the oxidizer from 21 to 40% results in a 1.6% reduction of the fuel consumption and the boiler gross efficiency increase of 1.6%. The further oxygen increase from 40 to 60% reduces the fuel consumption by 0.6% and the boiler gross efficiency increase by 0.6%. The further oxygen increases up to 95.6% increases the boiler gross efficiency by 0.4% and reduces the fuel consumption by 0.4%. Thus the oxygen content in the air increase up to 95.6% allows the boiler gross efficiency to increase up to 95.9% which is 3.1% higher than the mean efficiency of currently operating coal firing TPP boilers.

Figure 7. Specific fuel consumption vs O₂ content in the oxidizer.

Figure 8. Boiler gross efficiency vs O₂ content in the oxidizer.

Analysis of the coal firing STU auxiliary power consumption shows that the increase of O₂ content requires larger power consumption for its production in ASU (figure 9). An increase of O₂ content in oxidizer up to 95.6% requires the air separation unit power consumption up to 60 MW. The oxygen content increase of 1% requires 1.8% increase in the ASU power consumption.

Fuel combustion in the oxygen-enriched air increases the carbon dioxide content in the boiler flue gas which results in smaller power consumption for the carbon dioxide capture and storage (figure 10). When the O₂ content grows from 21 to 80% the mean power consumption for carbon dioxide capture and storage drops down by 2.5%. The largest drop of the power consumption of about 11% is seen at the oxygen content increase from 21 to 95.6%.
Figure 9. Power consumption for the oxygen production in ASU vs O₂ content in the oxidizer.

Figure 10. Specific losses for the CO₂ capture and storage vs O₂ content in oxidizer.

Despite the power consumption reduction for capture and storage that follows the oxygen content increase the cycle net efficiency drops down from 28.54 to 21.59% which is mostly caused by the oxygen consumption. At the oxygen content level of 95.6%, ASU power consumption amounts to 20% of the power produced by the steam turbine. The oxygen content change from 21 to 95.6% lowers the carbon dioxide capture and storage system power consumption by only 2.4% of the STU power production.

Finally, the application of oxygen-enriched air with 95.6% oxygen content reduces the TPP efficiency against the standard STU with carbon dioxide capture system by 11.4%.

Through the use of CCS and coal combustion in oxygen enriched air carbon dioxide emissions reduced to 150 g/kWh.

4. Conclusion
Increase of the oxygen content in oxidizer from 21 to 95.6% causes an increase from 21 to 70% of the carbon dioxide content in flue gas and 53.5% reduction of the heat losses with flue gas. Mass flow of coal supplied to the boiler drops down by 2.6% and the boiler gross efficiency grows from 93.4 to 95.9%.

Increase of the oxygen content in oxidizer causes an 11% reduction of the power consumption by carbon dioxide capture due to the higher carbon dioxide content in flue gas. Together with this increases the power consumption of oxygen production in air separation unit, which amounts to 20% of the total power in the thermal power plant operating on the 95.6% oxygen content in the oxidizer.

In total the increase of oxygen content reduces the steam turbine unit net efficiency from 28.54 to 21.59% because of the additional power consumption by the oxygen production. Thus the transition to fuel combustion in the oxygen-enriched air reduces the efficiency of the steam turbine thermal power plant equipped with the carbon dioxide capture and storage system by 11.4%.

Implementation of CCS with oxy-fuel combustion reduced the carbon dioxide emissions from 1100 g/kWh to 150 g/kWh. The use of ASU will allow for higher flame temperature in furnace, smaller air heater surface and carbon capture module. Thus it’s not obvious whether the cost of the TPP with CCS and ASU will be higher in comparison with the TPP with air combustion and CCS.

5. References
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