The use of air-bottoming cycle as a heat source for the carbon dioxide capture installation of a coal-fired power unit

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Abstract   The installations of CO_2 capture from flue gases using chemical absorption require a supply of large amounts of heat into the system. The most common heating medium is steam extracted from the cycle, which results in a decrease in the power unit efficiency. The use of heat needed for the desorption process from another source could be an option for this configuration. The paper presents an application of gas-air systems for the generation of extra amounts of energy and heat. Gas-air systems, referred to as the air bottoming cycle (ABC), are composed of a gas turbine powered by natural gas, air compressor and air turbine coupled to the system by means of a heat exchanger. Example configurations of gas-air systems are presented. The efficiency and power values, as well as heat fluxes of the systems under consideration are determined. For comparison purposes, the results of modelling a system consisting of a gas turbine and a regenerative exchanger are presented.

Keywords: Air bottoming cycle; Chemical absorption; CCS; Gas turbine; Gas-air systems

1   Introduction

In order to reduce CO_2 emissions, Poland, as well as other European Union member states, adopted the "3x20" climate and energy package. The basic

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assumptions of the package consist in a reduction of energy consumption by 20%, a 20% increase in energy generation from renewable sources, and a 20% reduction in CO_2 emissions compared to the year 1990. One of the methods to reduce emissions of CO_2 is its capture from flue gases in the process of chemical absorption. The process is very energy-consuming and it affects the coal-fired power unit efficiency considerably. However, the energy-consuming carbon dioxide capture system can be driven by thermal energy obtained from a different external source, without interfering with the steam cycle of the coal-fired power unit (Fig. 1).
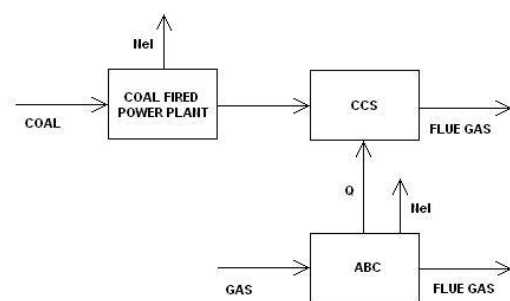

Figure 1. Gas-air system as a heat source for the carbon dioxide capture installation of a coal-fired power unit.

The issue is of vital importance, as this solution does not result in the need to upgrade the steam turbine or the regeneration system. The gas-steam systems [1–3] or the gas-air system (the air bottoming cycle – ABC), which was proposed in the late eighties [4–6], could be considered as a potential heat source. The choice between the ABC or the combined gas-steam cycle as the heat source ultimately results in fuel diversification for a given power plant. Gas-air systems can achieve a fairly high efficiency, mainly due to the progress made in the design of the blade profiles and sealing. Gas-air systems also have other advantages:

- improvement in the efficiency of the gas turbine cycle,

- potential to meet the peak demand for energy,

- no need to feed more water into the cycle,

- no emissions of harmful substances into environment,

- non-toxic cycle medium,

- application in many industries with the use of renewable sources of energy,

- lower investment costs compared to gas-steam systems [4].

An important component in terms of the efficiency of the entire configuration of the gas turbine with the ABC is the heat exchanger coupling the two systems. The most important parameters which have an impact on the optimum selection of the heat exchanger are pressure drops and temperature differences. High efficiencies of the cycle are achieved for small temperature differences in the heat exchanger, which result in its big dimensions. Other structural solutions that are possible to apply are shell-and-tube or plate heat exchangers. Gas-air systems can also be used as a potential improvement of the efficiency of simple power units with gas turbine operating at locations without access to large amounts of water, i.e. in offshore industry. Co-generative systems with air as the working medium, and systems of high temperature furnaces where the pre-heated air comes from the ABC [4–6], such as the furnaces for glass melting, are mentioned as well. Gas-air systems are also used in the food industry (industrial bakeries, powdered milk factories). In future, gas-air systems could be used in heat engineering, and they could also be the source of heat for carbon dioxide capture installations in steam power plants discussed in [7].

The paper presents the results of modelling a simple and a complex gas-air system. The efficiency of individual systems and the amount of heat that can be given up to the coal-fired power unit are determined. The results are compared to the system of a gas turbine with regeneration.

2   Technological structures under analysis

The basic data for the gas turbine adopted for the calculations are listed in Tab. 1 [8]. A simplified gas turbine model was applied using software Gate Cycle [9]. Figure 2 presents the diagram of the simple gas turbine unit coupled to an air turbine system through a heat exchanger treated as a air waste heat boiler with heat exchange efficiency of 96%. The following internal efficiencies of the machines were assumed:

- internal efficiency of compressor C$_2$ and C$_3$: $\eta_{C2} = \eta_{C3} = 88\%$,

- internal efficiency of air turbine T$_2$: $\eta_{T2} = 90\%$,

- efficiency of electricity G_2: $\eta_{G2} = 98\%$.

Table 1. Basic data of the Westinghouse turbine.

Westinghouse turbine, 501 series	
Model	501G
Commissioning year	1999
Power capacity, MW	249
Turbine inlet temperature, °C	1500
Mass flow, kg/s	559
Compression ratio	19.5
Flue gas outlet temperature, °C	600
Turbine-set efficiency, %	38.6
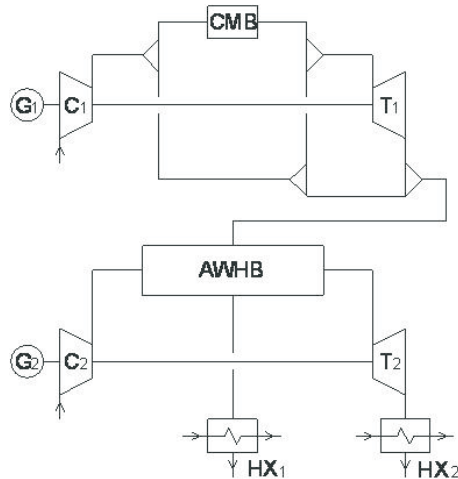
Figure 2. Simple gas-air system.

In the simple gas-air system a compressor with no intercooler, a heat exchanger AWHB (air waste heat boiler) coupling the gas and air systems, and the air turbine are used. The heat from flue gases and air is recovered in two heat exchangers, where heated water will be used in the CO_2 capture system of the coal-fired power unit. The mass flow of the water cooling heat exchangers HX_1 and HX_2 is selected so that the temperature of flue gases and air at the heat exchanger outlet will be at the level of

90 °C. The pinch between the cold inflow and hot outflow at heat exchangers HX_1 and HX_2 is maintained at approx. 10 °C, as the temperature of the re-circulating water is approx. 80 °C. Water is heated to the temperature of 135 °C. In the case of a flue gas-air heat exchanger, it is also important that the temperature does not drop below the dew point. Due to the possibility of corrosion, the direct flue gas – amine heat exchangers were not used. The typical operating temperatures for different kinds of amines such as methanolamine (MEA), diglycolamine (DEA), diglycolamine (DGA) or methyldiethanolamine (MDEA) are included in the range of 25–126 °C [10].

The complex gas-air system is composed of two compressors with an intercooler, a heat exchanger which couples the air and gas parts, and the air turbine (Fig. 3). The gas turbine used in the complex system is the same as the one used in the simple system. The heat exchanger effectiveness and the internal efficiencies are assumed at the same level as for the system of the simple gas turbine (efficiency of compressor C_3). Like in the simple system, two heat exchangers are used which heat the water for the installation of CO_2 capture from the flue gases of the coal-fired power unit. Similarly to the previous case, the mass flow of the water cooling heat exchangers HX_1 and HX_2 is selected so that the temperature of flue gases and air at the heat exchanger outlet will be at the level of 90 °C. The pinch between the cold inflow and hot outflow at heat exchangers HX_1 and HX_2 is maintained at approx. 10 °C, as the temperature of the water re-entering the heat exchangers is approx. 80 °C. The mass flow of the water cooling the intercooler of the compressors is selected so that the air temperature before the inlet to the second compressor will be at the level of 40 °C.

Figure 4 presents a diagram of the gas turbine system with regeneration and an extra heat exchanger heating the water for the needs of the coal-fired power unit CO_2 capture installation. It is an idealized model (due to the application of the expander cooling [11]), which is used only to compare the results with the simple system composed of a gas turbine coupled to the air turbine system by a heat exchanger.

In the system of a turbine with a regenerative heat exchanger there is an extra heat exchanger in order to heat the water which is the source of heat for the coal-fired power unit CO_2 capture installation. At the outlet, the temperature of flue gases is also maintained at the level of 90 °C. The pinch in regenerative exchanger HX_1 between the inlet of hot flue gases and the air outlet was maintained at the level of 50 °C.
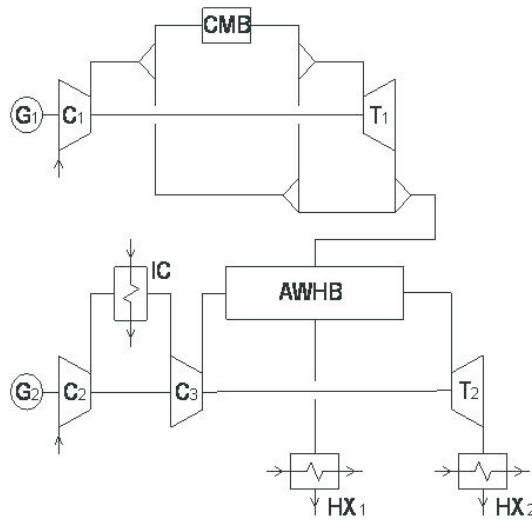
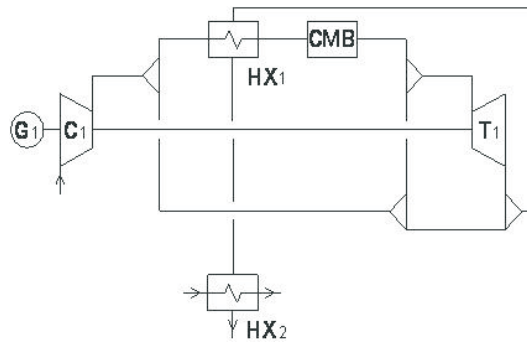Figure 3. Complex gas-air system with an intercooler.

Figure 4. Gas turbine with a regenerative heat exchanger.

3 Modelling results

Figure 5 presents the impact of the pressure ratio change in compressor C_2 on the electricity generation efficiency of the simple gas-air system. Characteristics were performed for three mass flow rates which corresponded to 75%, 100% and 125%, respectively, of the mass of the flue gases from the gas turbine unit. Maximum parameters were obtained for compression ratio π_2=5.1 and the air mass constituting 112.7% of flue gas mass m_{fg}. The electricity generation efficiency η_E then equals 47.35%. For the individual curves shown in Fig. 5 the range of pressure ratio is not identical. Keeping

the effectiveness of AWHB on 96% there is no possibilty to heat the water in HX$_1$ to 135 °C for lower values of pressure ratio in C$_2$ (flue gas outlet temp. is to low).
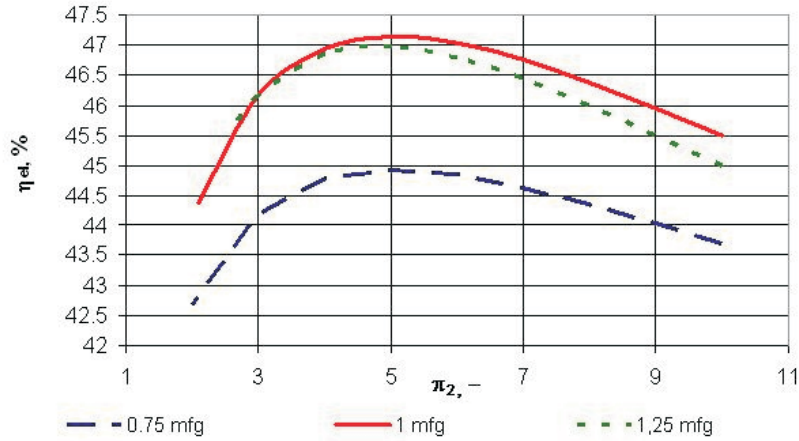

Figure 5. Electricity generation efficiency depending on the pressure ratio in the simple system.

Figure 6 presents the amount of heat that can be absorbed by water in heat exchangers HX$_1$ and HX$_2$ for the needs of the coal-fired power unit CO$_2$ capture installation (simple system). For the air mass flow for which the electricity generation efficiency was the highest, the value of the heat absorbed by water is not the highest. The heat that may be absorbed in the heat exchanger is given in relative units and defined by the dependence:

$$Q = \frac{Q_{HX1} + Q_{HX2}}{m_{fuel}LHV} \ , \tag{1}$$

where LHV is the lower heating value.

Figure 7 presents the impact of the pressure ratio change in compressor C$_3$ on the electricity generation efficiency of the complex gas-air system. Characteristics were performed for three mass flows which corresponded to 75%, 100% and 125%, respectively, of the mass flow of the flue gases from the gas turbine. Maximum parameters were obtained for compression ratio π_2=3 and π_3=2.65 and the air mass constituting 104.5% of flue gas mass m_{fg}. The electricity generation efficiency η_E then equals 48.96%. For the individual curves shown in Fig. 7 the range of pressure ratio is not identical.
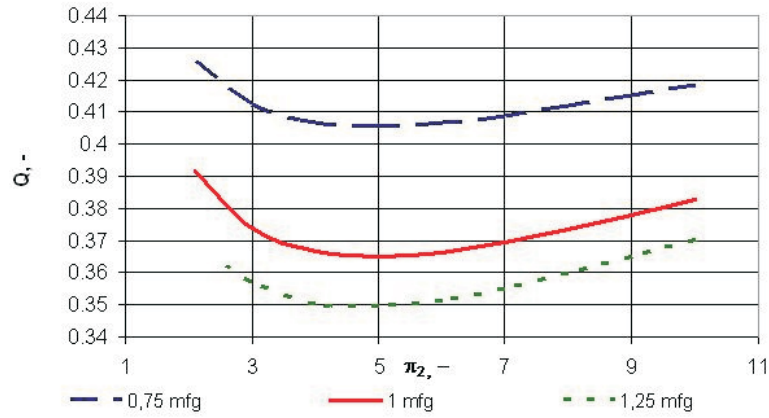
Figure 6. Heat absorbed by the medium in relation to the fuel chemical energy depending on the pressure ratio (heat exchangers HX_1 and HX_2) – simple system.
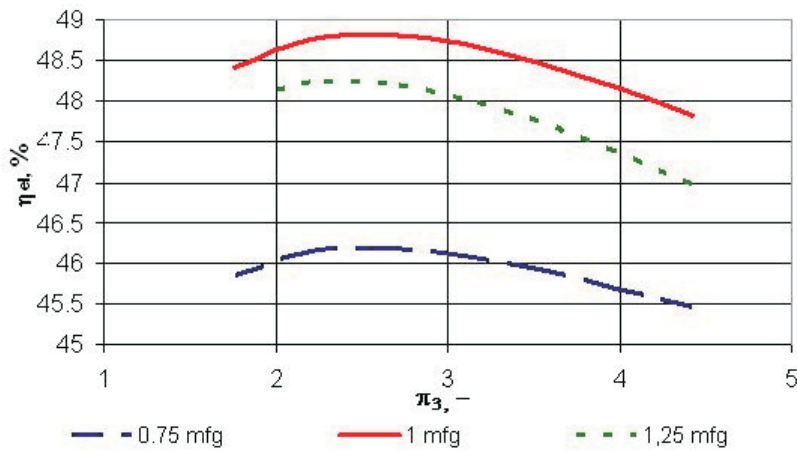

Figure 7. Electricity generation efficiency depending on the pressure ratio in the complex system.

This is a similar situation as in the simple gas-air system. Keeping the effectiveness of AWHB on 96% there is no possibilty to heat the water in HX_1 to 135 °C for lower values of pressure ratio in C_3 (flue gas outlet temp. is to low).

Figure 8 presents the amount of heat that can be absorbed by water in heat exchangers HX_1 and HX_2 for the needs of the coal-fired power unit CO_2 capture installation. For the air mass flow for which the electricity generation efficiency was the highest, the value of the heat absorbed by water is not the highest.
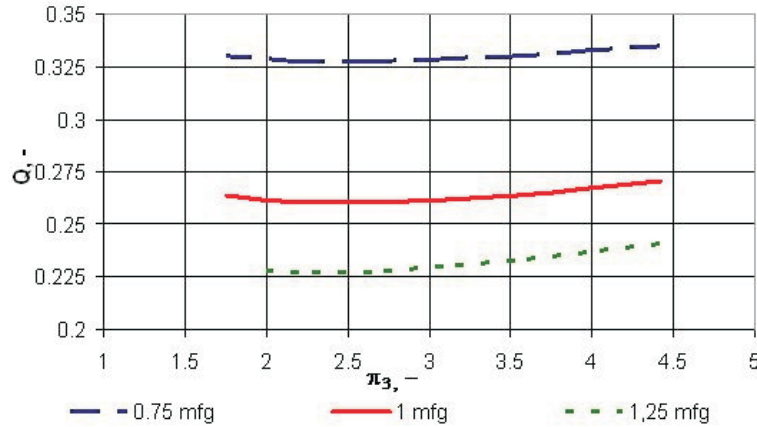

Figure 8. Heat absorbed by the medium in relation to the fuel chemical energy depending on the pressure ratio (heat exchangers HX_1 and HX_2) – complex system.

In the case of the turbine unit with regeneration, and changing compressor C_1 pressure ratio, the maximum efficiency and specific work of the system were determined, keeping the nominal air mass flow for the turbine unit (Fig. 9). The highest efficiency η_E=45.64% was obtained for the compression ratio π_1=9.47. Figure 10 presents the amount of heat that can be absorbed by water in exchanger HX_1 for the needs of the coal-fired power unit CO_2 capture installation (gas turbine system with regeneration).

The presented technological structures are characterized by high efficiencies and low HR (heat rate) per generation of 1kWh:

- simple system: HR=7603 kJ/kWh,

- complex system: HR=7351 kJ/kWh,

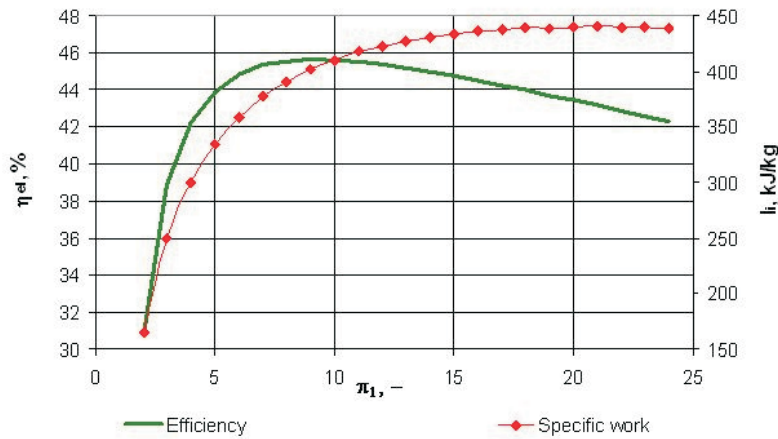- system with regeneration: HR=7888 kJ/kWh.

Figure 9. The system efficiency and specific work in relation to the mass flow of the fuel chemical energy (gas turbine system with regeneration).
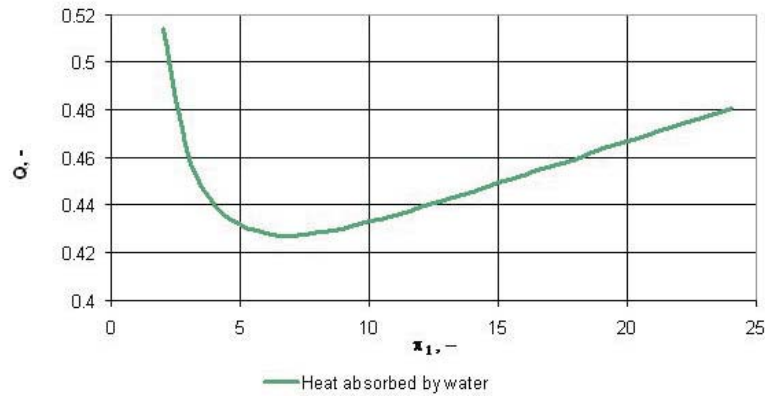

Figure 10. Heat absorbed by the medium in relation to the fuel chemical energy depending on the pressure ratio (heat exchanger HX_2) – system with regeneration.

4 System selection for a coal-fired power unit

The systems analyzed above are characterized by high efficiency, low heat rate for electricity generation and quite high power. Assuming that the potential system to provide heat for the CO_2 capture installation should be as efficient as possible, the heat flux which can be absorbed by water in heat exchangers is as follows:

- simple system: approx. 230 000 kW,

- complex system: approx. 160 000 kW,

- system with regeneration: approx. 211 700 kW.

Installations optimized in terms of efficiency can be successfully implemented for a 460 MW power unit. The process of CO_2 capture requires a high amount of heat. In the case of a 460 MW power unit, the cycle heat is approx. 950 MW. Then, two variants can be distinguished. The heat necessary to capture 1kg of CO_2 is:

- 2 MJ/kg of $CO_{2separated}$,

- 2.5 MJ/kg of $CO_{2separated}$

In the first case, assuming 100% CO_2 capture, 183 220 kW are needed. For this purpose, a turbine with heat regeneration can be used. Considering that water has to give up heat to another medium (typically – amine [10]), the system seems to be the most interesting one due to the surplus of power. In the case of increased heat consumption for CO_2 capture of the order of 2.5 MJ/kg of CO_2, the selection of the simple system is justified. The heat required to capture 100% of CO_2 will then be 229 000 kW. Assuming capture at such a high level, it will probably be necessary to select a simple system with a slightly lower efficiency, and – consequently – with a potentially bigger heat flux to give up. For example, in order to give up 235 000 kW of heat to the installation of CO_2 capture from flue gases of a 460 MW coal-fired power unit, it is necessary to reduce the efficiency of a simple system of a gas turbine coupled to an air turbine by approx. 1%, which entails increasing the heat rate per generation of 1 kWh by approx. 150 kJ/kWh.

5 Conclusions

The modelling resulted in systems characterized by high electricity generation efficiency. The amounts of heat which can be taken over by a coal-fired cycle testify to their great thermodynamic potential.

An important component which decides about the efficiency of the entire configuration is the heat exchanger (air waste-heat boiler) coupling the gas turbine system to the air turbine. The aim should be to minimize the pressure drop on part of both flue gases and air. Other structural solutions

that are possible to apply are shell-and-tube or plate heat exchangers. Plate heat exchangers are characterized by a smaller area of heat exchange and a smaller pressure drop of the two media. The avoided emissions achieved owing to the application of the air technology should also be mentioned. The implementation of this type of systems will depend on the results of the economic analysis and on the proper design of the said heat exchanger, which will be the subject of further research.

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