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A comparative thermodynamic, economic and risk analysis concerning implementation of oxy-combustion power plants integrated with cryogenic and hybrid air separation units

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ABSTRACT

This paper presents a comparison of two types of oxy-combustion power plant that differ from each other in terms of the method of oxygen separation. For the purpose of the analysis, detailed thermodynamic models of oxy-fuel power plants with gross power of approximately 460 MW were built. In the first variant (Case 1), the plant is integrated with a cryogenic air separation unit (ASU). In the second variant (Case 2), the plant is integrated with a hybrid membrane–cryogenic installation. The models were built and optimized using the GateCycle, Aspen Plus and Aspen Custom Modeller software packages and with the use of our own computational codes. The results of the thermodynamic evaluation of the systems, which primarily uses indicators such as the auxiliary power and efficiencies of the whole system and of the individual components that constitute the unit, are presented. Better plant performance is observed for Case 2, which has a net efficiency of electricity generation that is 1.1 percentage points greater than that of Case 1. For the selected structure of the system, an economic analysis of the solutions was made. This analysis accounts for different scenarios of the functioning of the Emission Trading Scheme and includes detailed estimates of the investment costs in both cases. As an indicator of profitability, the break-even price of electricity was used primarily. The results of the analysis for the assumptions made are presented in this paper. A system with a hybrid air separation unit has slightly better economic performance. The break-even price of electricity in this case is approximately 3.4 €/MW h less than for the system with a cryogenic unit. The main risk factors concerning implementation of such technologies were identified. The analysis of risk connected with the selection of these technologies was performed with the use of two methods – sensitivity analysis and a Monte Carlo method. The values of the probability were calculated, and the main results are presented and discussed in the paper.

1. Introduction

At present, European Union policy is focused on reducing greenhouse gases emissions into the atmosphere. Most anthropogenic emission results from combustion of fossil fuels. As a consequence, those countries in which the dominant fuel in power production is coal have been put in a difficult situation. It is necessary to introduce new energy generation technologies. Such technologies include not only those that use different renewable energy sources (RES), such as biomass, wind, water or solar in distributed energy systems, but also modern, advanced, central systems based on fossil fuels, such as the so-called clean coal technologies (CCT). One of the most important advantages of the latter type of system is the use of commercially available and well-known carbon fuel. Furthermore, there is no need for drastically changing the carbon economy into another. In many cases, solutions that operate using clean coal technologies allow the use of existing systems (power plants or combined heat and power plants).

In systems that are classified as clean coal technologies, along with operations that improve the efficiency of the conversion of the chemical energy of coal into electricity, a high-efficiency purification of flue gas is conducted; this purification also includes carbon dioxide removal. Among the available technologies of carbon dioxide capture, three main types should be distinguished: pre-combustion (in which CO_2 is captured from the gas before the combustion process), post-combustion (in which CO_2 is captured from the flue gas after combustion) and oxy-fuel combustion (in which the fuel is burned in oxygen) [1–5].

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Most of the operating installations, at different technological scales, use post-combustion technology [2,6]. This technology requires relatively little interference with the existing system and is therefore best suited for immediate implementation into the power sector. However, at present, the main disadvantage of this type of method is the high energy consumption of the chemical processes that are used for regeneration of the sorbent that absorbs carbon dioxide from the flue gases. Much effort has been made to develop new, less-intensive methods of separating CO_2 from flue gas. Very promising works include those that have investigated, e.g., adsorption technologies, membranes and innovative thermoacoustic methods [7–12].

Carbon dioxide separation from flue gases is not a problem in oxy-combustion systems, and with appropriate organization of the combustion process, this technology can also be implemented into existing units [13–19]. The main goal of oxy-combustion is to eliminate nitrogen from the flue gas. This result is achieved by replacing the air in the combustion process with high-purity oxygen. Consequently, the exhaust gas obtained consists mainly of carbon dioxide and water vapor; this exhaust gas is subjected to a relatively low-energy-consuming purification. The biggest drawback of oxy-combustion technology is the need for high-purity oxygen. Oxygen production is a well-known and long-used process, but so far, there was no need for production of oxygen on such a large scale. Currently, the most commonly used and virtually the only technologically mature method of oxygen production is separation from the air via a cryogenic process [14,20–22]. At present, the energy consumption of this type of system is in the range of 0.22–0.24 kW h/kgO_2; this level of energy consumption results in a significant decrease in the net efficiency of the power plants [13,19]. With time, other methods of oxygen production, including adsorption technologies, chemical looping and membrane technologies, and especially high-temperature ion-transport membranes, can become competitive [23–28,29]. Because of the high energy intensity of the process of oxygen production, it is justified to search for new opportunities to reduce the decrease in efficiency caused by the oxygen production. A significant decrease of energy consumption for this process will be possible with the use of high-temperature membranes [27,28,30,31]. However, they still need an important scale-up and verification of the operation in real conditions [32–34]. Combinations of various installations can also be well grounded because they can enable reductions in the energy consumption of the process while maintaining high quality of the final product and therefore high oxygen purity. They might also be more easily implemented into existing systems than new, emerging solutions. An example of such potentially useful hybrid technologies is a membrane–cryogenic installation, which consist of a low-temperature membrane, in which the air is enriched with oxygen, and a cryogenic component, in which the oxygen purity required for the combustion process is obtained. Such solutions are, so far, rarely proposed in the literature, however they are characterized by a high potential of decreasing energy consumption of the air separation process [25,35].

Systems that use oxy-combustion technology have not yet been implemented at the industrial scale. However, worldwide, there are many studies concerning the matter of combustion in oxygen in the laboratory or on technical scales being conducted (e.g., [36–39]). In 2008, a pilot project at the Schwarze Pumpe power plant in Germany was launched. This project has a capacity of 30 MWth [40,41]. Further implementation of this technology in the power sector will allow for verification of the conducted activities and also the investment costs incurred by the oxy-fuel power plants in the real world. Moreover, more studies are needed concerning thermodynamic optimization of the individual technological installations as well as of the whole structure of the power plant. New processes and technologies are to be developed and implemented. Not less important is optimization of the structure with respect to the economic aspect and risk analysis, that would show the influence of the different risk factors on the profitability of the investment in oxy-combustion systems. Such analysis are hardly met in the literature concerning oxy-combustion technology.

The main objective of this paper is an evaluation of the thermodynamic and economic validity and a risk analysis of the construction of two types of oxy-combustion power plant. In the first type, oxygen is produced in a classical cryogenic installation. In the second type, a hybrid membrane–cryogenic installation is used. In both variants, the exhaust gases are subjected to purification in a two-column phase-separation installation. In addition to the economic evaluation, a risk analysis connected with the implementation of these technologies was also performed, mainly using the sensitivity analysis and a Monte Carlo method.

2. Description of the analyzed oxy-combustion units

Oxy-combustion power plants include several technological installations, i.e., air separation unit (ASU), boiler island, steam cycle and flue gas conditioning installation. Each component of the integrated unit can differ depending on the system applied. A general schematic of an oxy-fuel plant with all the main mass and energy streams marked is presented in Fig. 1.

In this work, as a reference system, a plant that was based on the guidelines of the strategic research project co-realized by the authors, which is titled "Development of a technology for oxy-combustion pulverized-fuel and fluid boilers integrated with CO_2 capture", was analyzed. The reference plant in this project is an approximately 460 MW unit with a cryogenic air separation installation. In this paper, this variant is referred to as Case 1. In the second variant analyzed here (called Case 2), the cryogenic ASU from the reference plant was exchanged with a hybrid membrane–cryogenic installation. Within the system, a pulverized coal-fueled boiler operates producing supercritical steam. As a fuel, bituminous coal from the "Janina" coalmine in Poland is used. The coal has the following composition: 8.76% ash, 22.37% moisture, 52.63% carbon, 3.43% sulfur, 7.5% nitrogen, and 11.02% oxygen. A dry-recirculation loop of flue gas is realized within the boiler; this loop provides the appropriate conditions for conducting the combustion process. The flue gases are purified (de-dusted and desulfurized) and dried, and that part that is not subjected to the recirculation is directed to a carbon dioxide capture and compression installation. In this installation, carbon dioxide is first purified until it reaches a desired purity and then compressed to the pressure required for transport to a storage (or further utilization) place. Apart from the useful heat produced in the boiler, there are several places at which low-grade heat is produced (these areas are marked with a dashed line in Fig. 1) and can be usefully utilized in the system to increase the efficiency of the plant.

2.1. Boiler island and steam cycle

It was assumed in the analysis that in both cases, the same type of boiler operates. The boiler is a hard-coal-fed boiler that produces supercritical steam. The model of the boiler consists of a series of heat exchangers, including an evaporator, a live-steam superheater, a steam reheater, an economizer, a recycled flue gas heater, an oxidant heater, a dust removal installation and a drying installation. Additionally, there are also flue gas and oxygen fans and a coal mill. After leaving the oxidant heater, the flue gas is directed to a dust removal installation (electrostatic precipitator), desulfurization installation and (partial) drying installation. Then, part of the stream is recycled to ensure that the required fraction of oxy-