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Analysis of supercritical coal fired oxy combustion power plant with cryogenic oxygen unit and turbo-compressor

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A B S T R A C T

This paper reports the results of thermal, energy, exergy and economic analysis involving a hard coal fired power plant with a two-column cryogenic oxygen unit and operating in an oxy combustion process. As a novelty it was assumed that the auxiliary steam turbine drives the oxygen unit compressor and the bleeding steam for this purpose is extracted between intermediate- and low-pressure stage (ILS) of the main turbine. Calculations were performed to consider a number of alternative designs, in which the principal issue was to consider capacity and efficiency loss of the power plant resulting from the drive of the compressor from a cryogenic oxygen unit. The results showed that steam from ILS of the main turbine could be used for driving air separation unit (ASU) compressor. However, smaller loss of power and efficiency may be achieved with electrical supply of ASU. An application of oxy-fuel process to power plant will cause a decrease of gross efficiency in power unit by 12% points by using steam from ILS and 11% points by using electric motor for driving ASU. Profitability of oxy combustion technology will be achieved when the CO_2 emissions price reaches a minimum of 52 Euro/EUAs.

1. Introduction

CCS (carbon capture and storage) is a technology allowing for the reduction of CO_2 emissions into the atmosphere. It could be used as a technology of adapting power plants in which a significant reduction of CO_2 emissions is required. Oxy-fuel technology offers more advantages than other CO_2 capturing technologies since it can be adopted with regard to existing coal fired power plants [1,2]. The application of the oxy-fuel technology in power units is an idea guided by the necessity imposed by the need to fulfill EU regulations regarding the reduction of CO_2 emissions into the atmosphere [3–5]. A policy framework for climate and energy for European Union Member States in the period from 2020 to 2030 proposes a new reduction target for domestic greenhouse gas emissions of 40% compared to 1990 [6], which could be difficult to achieve without using of improvement technologies like carbon capture and storage. Oxy combustion technology also promises lower NO_x emission level in the atmosphere [1,7]. The studies in Refs. [1,8,9] showed that oxy combustion is a feasible process from the technical and economic perspective only when considerable reduction in the CO_2 emissions will ensue. However the cost of electricity generation with CO_2 capture is higher than the cost of electricity generation without it and it depends on a number of technical and economic factors [10]. Recently, a number of researchers performed calculations to analyze the operation of an oxy-combustion power plant with results that shows possibilities of this system improvements [11–16]. A technical and economic evaluation for three power plants with the capacity of 300–1000 MW was performed (subcritical, supercritical and ultra-supercritical) in Ref. [17]. Indicator-based parameters associated with energy consumption in an oxygen producing unit are typically used in the studies concerned with coal fired power plants involving an oxygen generating system. The studies involving a thermal analysis of coal fired oxy combustion power plants with a cryogenic compressor oxygen unit are scarce to this date [18–21]. Additionally, various papers undertake a technical and economic analysis of the oxy combustion technology [22–27]. In general, the results in the literature stress that the application of the oxy-fuel technology will decrease net power output by approximately 25%, the cost of electricity will increase by 30%–50%, whereas the CO_2

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avoidance cost will reach approximately $30/Mg_{CO2}. The results found in Refs. [17,22,24–27] also indicate that each case of coal fired power plant upgraded to the oxy combustion technology should be analyzed individually.

The purity of oxygen at the level of at least 95% needs to be secured for suitable effects resulting from the oxy combustion process [28,29]. The flow of the technical oxygen with such parameters for the considered power plant could be derived only by application of the cryogenic technique [30]. Combustion process in the technical oxygen environment results in a significant increase of combustion temperature, significantly above 1100 K. Consequently, this would be the source of problems with the strength of materials used for boiler design as well as with softening behavior of coal ash. In addition, there is a necessity of a suitable control of the recirculation process of the combustion gases in order to reduce the temperature in the combustion chamber. However, the concentration of CO_2 at a level of as much as 98% can be obtained [31,32]. This high CO_2 concentration in the combustion gases enables the process of sequestration, i.e. capture, transport, and finally long-term CO_2 storage or use of this gas in another process. The sources of ideas regarding capture and storage of CO_2 are to be sought in the managements of petroleum and gas companies, who have to spend considerable sums of money to restore these areas to the environment in an unharmed condition in accordance with EU regulations, in particular the ones conforming to European Union Emissions Trading Scheme.

It is noticed, that particularly, in the present literature there are no results regarding various alternatives of coupling these installations using steam bleed from one of the extractions in the main turbine, what is presented in this paper. This study took up a comparison between conventional air fired combustion process and oxy combustion technology. The results of such calculations as the efficiency of a power unit, net electricity output and cost of electricity production from an oxy combustion power plant will be considerably dependent on the technology, power plant design and its adaptation level by adding extra features, as well as configurations in the system of oxygen production. The method of coupling power plant with an installation of oxygen production as well as its structure are areas of special importance here. In order to obtain combustion parameters close to the ones in the traditional fluidized bed combustion process, a mixture of technical oxygen and recirculated combustion gases consisting of mainly CO2 was assumed (Fig. 1).

The results of calculations are presented with the aim to determine losses resulting from the energy consuming process of oxygen production. These losses lead to a decrease of the electricity output and efficiency of a power plant. An integration of a power plant and an oxygen unit may be realized by application of a turbocompressor with an auxiliary turbine with steam extracted from the exhaust of the main turbine. The analysis of various places of steam fed from the main turbine exhaust to supply additional turbine powering air compressor in oxygen production unit is presented. In addition, calculations for the electric drive of the air compressor in the oxygen unit were performed. Detailed studies concerns also the possibility of energy recovery from the turbodetander in the oxygen unit and the heat from the compressed air through an additional heat exchanger. Thermal, energy and exergy analysis for the designed oxy combustion power plant was done. Moreover, the economic study to analyze the economic effects of adopting oxy combustion process for supercritical coal fired power plant are designed here. Results of findings are presented for different power unit loading.

2. Modeling

In this section it is presented the methodology of system modeling including the all considered capabilities. It covers the reference power unit with supercritical parameters, two-column oxygen unit and the oxyfuel power plant in different configurations.

2.1. Mathematical model of a selected coal fired power plant adapted to the oxy combustion process

In order to undertake a thermal analysis of power plant operation in variable conditions, resulting from oxygen combustion, a mathematical model was developed with regard to a power unit with the capacity of 463 MW. The mathematical model consists of substance and energy balance equations for its basic components and junctions as well as of H_2O state equations and characteristics of the power unit elements in the form of equations [33–36]. The substance and energy balance equations were formulated by adopting a few standard simplifying assumptions. The resulting set of 335 equations was solved using EES (Engineering Equation Solver). This is a computer code which involves the simulation of a power plant together with evaluation the impact of additional components needed for the realization of the oxy combustion process. This professional software is commonly used for a complex of thermal calculations especially for the modeling of nonlinear equations. Internal data library allows to create modeling on the basis of the libraries of properties of H_2O, as well as, e.g. real gases and refrigerants. Equations are solved based on a version of the algorithm of Newton, characterized by the following features: (a) Jacobian components are determined by means of numerical calculations, (b) system of equations is divided into blocks in order to accelerate convergence, the division is done by probing Jacobian method Tarjan [37].

The power needed to drive the oxygen unit air compressor is derived from the auxiliary turbine while the steam into this turbine is fed from the main turbine exhaust. It results in the variable characteristics of the power unit; yet, the first of them is associated with the decrease of electricity output and its efficiency. For comparison purposes alternative calculations were performed for the electric drive of the air compressor in the oxygen unit.

2.2. Selection of the structure of the coal fired power unit and its basic components

The simplified diagram of the coal fired power plant unit investigated in this paper is presented in Fig. 2. The analyzed power plant unit has a gross capacity of 463 MW (net electric power 439 MW) and is operating under supercritical parameters of steam driving the main turbine. Steam from the fluidized boiler expands in the high pressure stage of the turbine and is then reversed to the boiler for secondary preheating. The main steam turbine consists of high pressure (HP), intermediate pressure (IP) and low pressure (LP) stages. The HP stage has two steam extractions: S7 from which steam is extracted to feed HP2 heat exchanger and S8 with steam bleed into HP3 heat exchanger. The IP stage has three steam extractions with steam bleed from S6 extraction into steam cooler (SC) and then to HP1 heat exchanger. Steam from S5 extraction flows into DEA deaerator with feedwater tank FWT and partly to the auxiliary turbine AT and to drive the feedwater pump (P2) while steam from S4 extraction is used to feed LP4 heat exchanger. The LP stage has also three steam extractions (S3 ÷ S1) with steam bleed from them used to feed LP3 ÷ LP1 heat exchangers, respectively. HP1 ÷ HP3 and SC heat exchangers form the high pressure stages of the regenerative system of the main turbine while S1 ÷ S3 heat