Applied Thermal Engineering 103 (2016) 274–281

Contents lists available at ScienceDirect

Applied Thermal Engineering

journal homepage: www.elsevier.com/locate/apthermeng

Research Paper

Minimization of CO_2 capture energy penalty in second generation oxy-fuel power plants

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HIGHLIGHTS

- A heat integration methodology based on pinch analysis has been developed.
- This methodology has been applied to a 2nd generation oxy-fuel power plant concept.
- An oxy-fuel power plant with a feasible heat exchangers network has been proposed.
- Penalty has been reduced 3.3 efficiency points with a plant net efficiency of 36.4%.

ARTICLE INFO

Article history:
Received 2 March 2016
Accepted 21 April 2016
Available online 23 April 2016

Keywords:
Oxy-fuel combustion
CO_2 capture
Heat integration
Energy penalty
Power plant efficiency

ABSTRACT

Oxy-combustion is one of the most promising technologies to reduce CO_2 emissions from coal-fired power plants. Nevertheless, as CO_2 capture system there is an important energy penalty and efficiency of the overall power plant substantially decreases. It is well accepted that the application of first generation post-combustion and oxy-fuel combustion technologies reduce the power plant efficiency in 10–12 efficiency points.

Air separation unit (ASU) and compression and purification unit (CPU) are the main energy consumers in the oxy-fuel process. Moreover, the oxidant flow, which is a mixture of O_2 and recirculated flue gases (RFG), requires a high heating demand in order to preheat it before the boiler inlet.

This paper presents a methodology for the minimization of the energy penalty in oxy-fuel power plants that also includes ASU and CPU optimized designs with lower energy consumption, a boiler working with a high oxygen concentration (up to $40\%_v$) in oxidant and waste energy integrated with a new designed steam cycle. Results show an important increase in power plant net efficiency (36.42%, LHV basis) regarding oxy-fuel reference power plant (32.91%). As a consequence, energy penalty can be reduced from original 10.5 points to 7.3 points.

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1. Introduction

Currently, one of the challenges of the carbon capture and storage (CCS) technologies is to find ways to reduce the energy penalty and increase the efficiency of the energy processes.

While the efficiency of supercritical air-fired thermal power plants can reach 45% [1], the efficiency significantly reduces by 12% when the oxy-fuel CCS components are added to capture the CO_2 [2,3]. This is a significant reduction in the overall efficiency and will drastically increase the fuel consumption for unit power produced resulting in increased cost of electricity and further CO_2 emissions. Other studies have reduced this penalty to around 11 efficiency points [4,5], therefore significant improvement in the efficiencies of the additional CCS units and in the oxy-fuel boiler are necessary to make the process economically feasible. Main strategies to tackle this problem include: (i) improvements in the Air Separation Unit (ASU) and/or Carbon Processing Unit (CPU);

Abbreviations: ASU, air separation unit; *CAPEX*, capital expenditure ; *CCS*, carbon capture and storage; *CFB*, circulating fluidized bed; *CP*, heat capacity flow rate; *CPU*, CO_2 compression and purification unit; *HEN*, heat exchanger network; *HP*, high pressure; *LHV*, lower heating value; *RFG*, recirculated flue gas; U, utilities.

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http://dx.doi.org/10.1016/j.applthermaleng.2016.04.116
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(ii) the optimization of the flue gas recycle; and (iii) the energy integration to use the residual heat from different parts of the system.

Oxygen production is one of the main power consumers in an oxy-fuel power plant. First studies considered a value of 220 kW h/tO_2 [3] but this value has been reduced as the cycles developed in the 1990s were not fully adapted for oxy-fuel combustion applications [6]. Current values make possible an important reduction in the penalty associated with ASU. It has been reported values as low as 140 kW h/tO_2 by 2015 and an estimation of 120 kW h/tO_2 by 2020 including credits (utilization of waste heat internally in the process) [7]. CPU, including CO_2 compression, is another important power consumer, around 7.7% of gross power is used in this equipment [6] and reduction of this value is more difficult than for ASU.

Flue gas recycle reduction has been analysed as a measure to increase efficiency mainly in pulverized coal power plants. Gao et al. [8] propose to use additional heat transfer surfaces for gas temperature controlling in the boiler furnace instead of high recirculated flue gas flows. A comparative analysis between dry, semi-dry and wet recirculation recycle has shown the possibility to reduce the penalty to around 10 efficiency points [9]. In addition, exergy analysis has been carried out for the design of an optimum flue gas recycle process [10]. For circulating fluidized bed the literature is scarce but Weng et al. reported a detailed analysis of the flue gas recirculation with overall efficiency penalty of 8.8 points [11]. Niva et al. developed control strategies for flue gas recirculation in Circulating Fluidized Beds (CFB) [12].

Simulation and energy integration is the most suitable method to achieve an important overall reduction of the energy penalty in CCS. Evidently, optimized systems (ASU, CPU, flue gas recycle) should be included to obtain an important efficiency augmentation. Nevertheless, most of the times for obtaining optimized system layouts, is necessary to think about an overall problem. Overall optimization results may not be a merge of optimized systems. Several references have dealt with energy integration [13–15] and energy and mass balance for pulverized coal oxy-fuel power plants [16]. Kakaras et al. published a set of three papers with a power plant layout for pulverized coal oxy-fuel combustion. In the first paper [14], reference plant was a 360 MW_e gross power with a net efficiency of 40.83%. Oxy-fuel power plant design includes an evaluation of the new boiler with increased heat transfer by radiation and convection and an integration of waste heat in a supercritical steam power cycle with some optimistic assumptions (CO_2 and air intercooling down to 21 °C in CPU and ASU). As a result, oxy-fuel power plant net efficiency was 32.29% (gross 53.15%) that is only 8.5 efficiency point lower than reference air power plant. Evidently, for a retrofit option the energy integration is limited and the boiler could not be redesigned to optimize the use of waste heat and the net efficiency reduces to 28.76% [15]. In any case, calculation showed good economic feasibility with moderate cost of electricity and low economic cost per tonne of CO_2 avoided [13]. Similar integration and economic values were obtained by [17,18] that analysed four oxy-fuel possibilities for Romania case [17], with a minimum efficiency penalty about 9 points, and a comparison with other technologies [18].

Despite the important advantages and good performance of some pilot experiences [19–22], the application of oxy-fuel technology with Circulating Fluidized Beds has not been widely studied. In the past, first oxy-fuel technology reviews did not mention this application or it was barely cited but lately its importance has been clearly explained [23–25]. There are some special features in the boiler design, as the incorporation of external heat exchangers [26], which affects the steam cycle layout especially when high oxygen concentrations are used in the boiler [27].

Lately, the utilization of high O_2 concentrations in oxy-fuel combustion (more than 30%) has been proposed as proved concept to reduce flue gas recirculation and energy penalty [28]. This paper aims to present a methodology to integrate the residual heats in an oxy-fuel CFB power plant and optimize the whole concept leading to the development of a 2nd generation oxy-fuel power plants with minimum CCS energy penalty. New ASU and CPU concepts that involve optimized configurations have been defined. CFB boiler has been designed to burn with a high oxygen concentration (40% by volume).

2. Heat integration methodology

One of the main drawbacks to CO_2 capture development refers to the high energy penalty of the process. In an oxy-fuel power plant facility, the complexity of the process along with the cooling and heating requirement at different temperature levels makes mandatory the design of a complete heat integration methodology with the aim to reduce this CO_2 capture energy penalty. Pinch analysis can tackle this problem by defining an optimized Heat Exchanger Network (HEN).

In order to address the problem, pinch analysis has been applied to evaluate the heat recovery options and to design the optimized heat exchanger network. In addition, an Aspen Plus simulation model has been proposed to simulate the whole power plant, including all the subsystems and the new HEN. Fig. 1 shows heat integration methodology scheme.

First stage of the process consists of the definition of the reference state-of-the-art oxy-fuel power plant. This reference power plant is simulated to obtain its efficiency and the energy penalty. Once reference power plant is set and initial net efficiency is established, the involved streams in pinch analysis must be selected and defined (mass flow, CP, source temperature, objective temperature). Minimum temperature difference is then chosen and cooling and heating demands can be calculated by running the pinch analysis. Afterwards, a Heat Exchanger Network is built and it is included in previous simulation. The new configuration is modelled and finally power output and efficiency results are available. Sensitivity analyses can be later implemented in order to complete the whole heat integration process.

3. Case study

3.1. Reference oxy-fuel power plant

In order to apply the heat integration methodology previously described, a case study has been accomplished. Reference oxy-fuel power plant includes an air separation unit for oxygen generation. For the case study, an oxygen mass flow of 128.6 kg/s is produced in the ASU plant with 96.6% purity. In addition, the oxy-fuel power plant includes a carbon purification unit with CO_2 compression that is able to process up to 145 kg/s of 99% pure CO_2 mass flow. The boiler is a circulating fluidized boiler that can operate with an oxygen range between 25% and 40% (in volume). Depending on the boiler oxygen concentration, the recirculated flue gas parameters are modified and new mass flow and temperature levels have to be taken into account in the heat integration process. In this initial reference case a 25% oxygen concentration has been selected. The power cycle includes a steam turbine with a single reheat, four high-pressure heaters, a deaerator and three low-pressure heaters. Steam is expanded up to a condenser pressure of 0.05 bar. The predesign of the steam cycle has been carried out according to the state-of-the-art for supercritical power plants. Fig. 2 shows the complete scheme for the reference power plant.

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