Applied Energy 132 (2014) 127–136

Contents lists available at ScienceDirect

Applied Energy

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

Oxy-fired fluidized bed combustors with a flexible power output using circulating solids for thermal energy storage

B. Arias [a,*], Y.A. Criado [a], A. Sanchez-Biezma [b], J.C. Abanades [a]

[a] Instituto Nacional del Carbón, CSIC-INCAR, C/Francisco Pintado Fe 26, 33011 Oviedo, Spain
[b] Endesa Generación, Ribera del Loira 60, 28042 Madrid, Spain

HIGHLIGHTS

- The energy storage system is composed of two silos connected to a CFB combustor.
- Power output can be varied without modifying the fuel firing rate and the flow of O_2.
- A large amount of power can be generated even with a small CFB combustor.

ARTICLE INFO

Article history:
Received 21 January 2014
Received in revised form 12 May 2014
Accepted 29 June 2014

Keywords:
CO_2 capture
Oxy-fired combustion
Energy storage
Circulating fluidized bed
Power plant

ABSTRACT

This paper presents a power plant concept based on an oxy-fired circulating fluidized bed combustor (oxy-CFBC) combined with thermal energy storage on a large scale. The concept exploits to full advantage the large circulation flows of high temperature solids that are characteristic of these systems. Two solid storage silos (one for high temperature and the other for low temperature solids) connected to the oxy-fired CFBC allow variability in power output without the need to modify the fuel firing rate and/or the mass flow of O_2 to the combustor. During the periods of high power demand the system can deliver additional thermal power by extracting heat from a series of fluidized bed heat exchangers fed with solids from the high temperature silo. Likewise, during period of low power demand, the thermal power output can be reduced by using the energy released in the combustor to heat up the low temperature solids on their way from the low temperature silo to the oxy-CFBC and storing them in the high temperature silo located below the cyclone. A preliminary economic analysis of two designs indicates that this highly flexible system could make this type of power plant more competitive in the electricity markets where fossil fuels with CCS will be required to respond to a large variability in power output.

1. Introduction

Fossil fuels will continue to play a major role in meeting the world's energy needs because of their very competitive cost, widespread distribution and the massive infrastructure available for burning them. CO_2 capture and storage (CCS) technologies are considered to be one of the least-cost options for mitigating climate change [1]. In addition, CO_2 capture and storage is the only low carbon technology that can make the vast economic assets linked to fossil carbon reserves or unburnable carbon compatible [2,3].

Moreover, it is becoming increasingly common in the major electricity markets to operate fossil fuel power plants with large load changes and even periods of complete shut down, in order to be able to adjust to the variability in energy demand and to the increasing share of renewables in the electricity mix. Renewable energies like wind and solar power are characterized by their intermittency, so they need energy storage systems and/or back up infrastructures to adapt their supply to demand [4]. The use of air-fired fossil power plants to accommodate changes between minimum and full load by ramping up and down is a common practice [5]. However, there are substantial energy and economic penalties when the power generation equipment is forced to operate with load changes and offline periods [6–8]. In addition, the cycling mode of operation in fossil fuel power plants leads to low capacity factors, which obviously increases the cost of electricity compared to when operating at base-load. All these problems are aggravated in power plants with CCS because these are complex and integrated systems that are inherently capital intensive [1,9,10] and better adapted to base load operation. However, since the flexible mode of operation may be imposed by regulators or market conditions, there is a growing interest in developing CCS systems that allow a wide flexibility

* Corresponding author. Tel.: +34 985119057; fax: +34 985 297662.
E-mail address: borja@incar.csic.es (B. Arias).

http://dx.doi.org/10.1016/j.apenergy.2014.06.074
0306-2619/

and load change [11–14] and ensure minimum impact on the unit of product (i.e., the kW h_e and/or the tonne of CO_2 avoided).

For post-combustion CO_2 capture systems that employ amine-based solvents, the use of tanks has been proposed as a means of storing the rich solvent leaving the absorber during peak demand periods [15]. This allows the regeneration of the solvent and the compression of the CO_2 captured to be postponed to periods of low power demand. During the high power demand periods, the net power plant output is increased as the energy penalty associated with the consumption of the steam in the regenerator and electricity during the compression of CO_2 is avoided [16]. However, even the storage of solvent for a few hours of operation will require the storage of large masses of costly amine.

In pre-combustion CO_2 capture systems, the power generation block can be decoupled from hydrogen production by using an intermediate hydrogen storage system provided that a geological suitable structure is available [11,15]. More commonly, the clean syngas can be diverted in polygeneration systems to a chemical production line for the production of fuels such as methanol or dimethyl ether when there is a low power demand [17].

For oxy-fuel combustion power plant systems, the use of oxygen cryogenic tanks for backup storage [15,18] has been proposed to overcome the flexibility constraints during boiler load changes imposed by the slow response of the air separation unit (ASU). This increases the cost of the oxygen produced, mainly as a result of the additional energy requirements for the liquefaction and re-evaporation of the oxygen. Another proposal for improving the flexibility of oxy-fired systems is to design a combustor that is able to operate in oxy-fuel or air mode. The combustor could then operate in air mode during high demand peaks to avoid the high energy penalty associated with consumption in the ASU and CPU [19]. However, this solution implies a substantial amount of carbon leakage, as CO_2 is emitted during air combustion periods.

One of the possible approaches to introduce flexibility in power plants would be to build an energy storage system within the power plant boundary. This would allow variability in power output irrespective of the thermal power input. The idea of implanting an energy storage system inside the fossil fuel power plant is not new and several conceptual designs were proposed in the late 70s [20]. For example, Drost et al. [21] proposed a concept in which a coal-fired power plant heats up molten salt from 288 °C to 566 °C and stores the salt in a high-temperature tank during periods of low electricity demand. During peak demand periods, the hot salt is withdrawn from the high temperature tank and used as a heat source for a steam generator after which the cold molten salt is returned to a low temperature tank (at 288 °C). Molten salt thermal energy storage systems are today commercially available and employed in concentrated solar power plants [22]. Another type of system for this kind of solar plant is to use moving solids to store energy as latent heat [23–25]. These systems typically consist of two silos for storing solids at different temperatures and at least one heat exchanger to transfer the energy from the solar field to the solids during the charging periods and another heat exchanger to release the energy stored in the solids to a working fluid during discharge periods [23–25].

Another example of thermal energy storage in fossil fuel power plants is to use hot water tanks integrated within the steam cycle [21]. During high demand peaks, the hot water can be discharged into the cycle to avoid steam consumption in the water preheaters. This can boost the amount power delivered and allow primary and secondary frequency support responses [26]. The use of rapid changes in the solids circulation flows and inventories in high temperature solid looping cycles for CCS has also been proposed recently for the same purpose [27]. However, these solutions are intended for very small quantities of energy and cannot be considered effective for large-scale energy storage systems.

The oxy-fired CFBC concept [28] presented in this work incorporates a large-scale thermal energy storage system that exploits the inherent capacity of circulating fluidized bed combustors to handle and circulate large flows of solids at high temperature. Oxy-fired CFBC technology has been developed very rapidly in recent years [29–31] due to its similarity to existing commercial air-combustion systems, that have already reached scales of up to 600 MW_e [32]. By exploiting the elements already present in CFBC power plants, a basic economic analysis of the proposed system has been carried out in order to compare its expected electricity costs with those of equivalent oxy-CFBC and air-CFBC power plants forced to operate with low capacity factors.

2. Process description

The oxy-fired CFBC power plant concept proposed in this work is represented in Fig. 1. It is composed of several elements (marked in grey) that are common to all oxy-fired CFBC power plants: a CFB combustor, cyclones, convective heat exchangers and air preheaters (all marked with the symbol of HX_1 to simplify the diagram), an external fluidized bed heat exchanger ($FBHX_1$), an air separation unit (ASU) and CO_2 compression and purification units (CPU). The combustor chamber of the power plant depicted in Fig. 1 is assumed to operate in adiabatic conditions by extracting as much heat as possible from the combustor chamber. Maximum extraction is achieved by using the circulating solids ($G_{S\ CFBC}$) as a heat carrier. Although not a common practice in existing boilers (where a substantial fraction of the power released during the combustion is recovered inside the combustor chamber by transferring the heat to water pipes or wing walls within the combustor), this heat management option is feasible with the currently available CFBC technology and it is also a design option for oxy-CFB boilers [29,33–37] thanks to the large heat carrying capacity of the solids circulating in and out the combustor. In these conditions, the external fluidized bed heat exchanger ($FBHX_1$) is one of the main thermal power outputs from the combustion system of Fig. 1 to the steam cycle (not shown in the figure for simplicity). The fluidized bed heat exchanger is located in the return path of a fraction of circulating solids (labelled as stream 4 in Fig. 1). Another stream of circulating solids (stream 5) can by-pass the heat exchanger and enter the

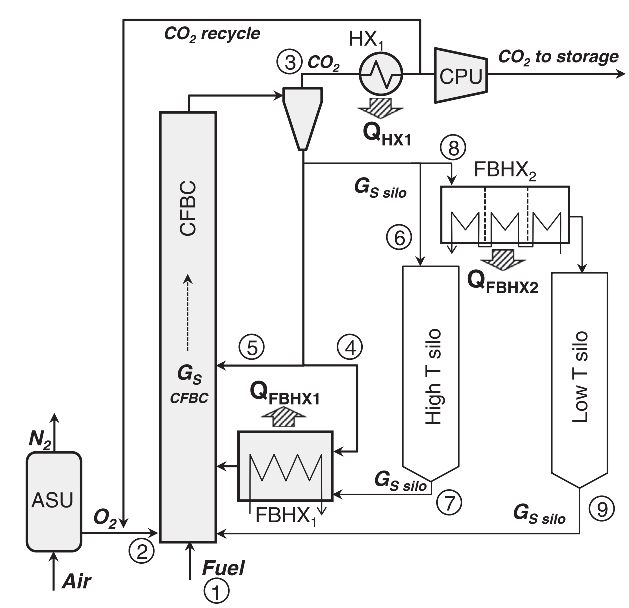

Fig. 1. Scheme of the oxy-CFBC power plant concept with energy storage as proposed in this work.