Applied Energy 111 (2013) 690–700

Contents lists available at SciVerse ScienceDirect

Applied Energy

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

Design and analysis of heat exchanger networks for integrated Ca-looping systems

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HIGHLIGHTS

- Heat integration is essential to minimize energy penalties in calcium looping cycles.
- A design and analysis of four heat exchanger networks is stated.
- New design with higher power, lower costs and lower destroyed exergy than base case.

ARTICLE INFO

Article history:
Received 22 November 2012
Received in revised form 29 April 2013
Accepted 17 May 2013

Keywords:
CO_2 capture
Ca-looping
Heat integration
Pinch
Exergy

ABSTRACT

One of the main challenges of carbon capture and storage technologies deals with the energy penalty associated with CO_2 separation and compression processes. Thus, heat integration plays an essential role in the improvement of these systems' efficiencies. CO_2 capture systems based on Ca-looping process present a great potential for residual heat integration with a new supercritical power plant. The pinch methodology is applied in this study to define the minimum energy requirements of the process and to design four configurations for the required heat exchanger network. The Second Law of Thermodynamics represents a powerful tool for reducing the energy demand since identifying the exergy losses of the system serves to allocate inefficiencies. In parallel, an economic analysis is required to asses the cost reduction achieved by each configuration. This work presents a combination of pinch methodology with economic and exergetic analyses to select the more appropriate configuration of heat exchanger network. The lower costs and minor destroyed exergy obtained for the best proposed network result in a of 0.91% global energy efficiency increase.

1. Introduction

The reduction of energy consumption by improving the efficiency of industrial processes is an essential mechanism to minimize global warming. CO_2 capture processes may significantly diminish the greenhouse gas emissions; although one of their main drawbacks is the high energy penalty. Energy optimization is, therefore, crucial for CO_2 capture development.

Among the different proposed technologies, high temperature looping cycles represent an option with wide integration capabilities, which would limit this energy penalty to 10–12 efficiency points [1,2]. Calcium looping cycles take advantage of the reversible decomposition of $CaCO_3$ combining the low sorbent cost, the absence of flue gas treatment and the possibility of integration with power plants or cement industry [3–5].

Shimizu et al. [6] first proposed the dual circulating fluidized bed configuration for implementing the Ca-looping in post-combustion. A flowsheet diagram is shown in Fig. 1. Flue gas (1) from a power plant is fed to the first reactor, where the carbonation reaction takes place, at around 650 °C, and a percentage of the CO_2 is captured exothermically. Afterwards, flue gas is addressed to the stack as clean gas (2). A stream of partially carbonated solids (3) is then directed to the second reactor (calciner) where the sorbent is regenerated (4), at 930 °C, releasing a highly concentrated CO_2 stream (5) that is conducted to compression, transport and storage.

The energy required for sorbent regeneration and for heating up the particles coming into the calciner [7] is supplied by oxy-combustion of fuel in the reactor itself. The air separation unit (ASU) demanded for this step also introduces a strong energy penalty.

Natural sorbents like limestone and dolomite rapidly deactivate, and different conditions (SO_2 in flue gas [8] or particle sintering [9]) may influence that. In consequence, are needed large make-up flows (stream 7, Fig. 1) of fresh material to compensate sorbent degradation, inert accumulation, and elutriation of fines [10–12]. Different sorbent pretreatments are under study to in-

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http://dx.doi.org/10.1016/j.apenergy.2013.05.044

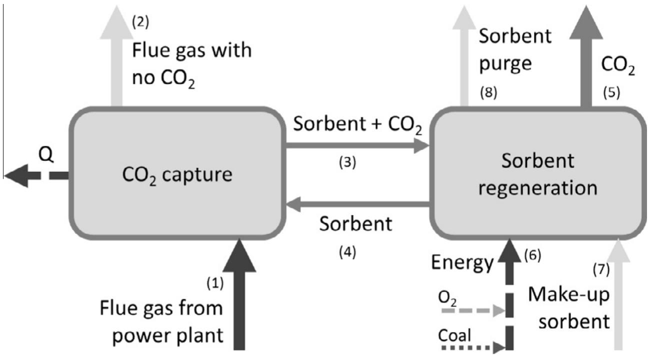

Fig. 1. Carbonation-calcination loop flowsheet.

crease their capacity [13,14]. An increase of the sorbent/CO_2 ratio and the make-up flow of fresh material counterbalance the low residual conversion of the sorbent reached after a high number of carbonation/calcination cycles. However, a high Ca/CO_2 ratio also increases energy requirements in the system due to the larger sorbent circulation between reactors.

In the Ca-looping process, there exist high temperature streams which may be used to retrofit the existing power plant [15–17], or to drive a new steam cycle [1,18,19], increasing the total net power output of the system and diminishing energy penalties. These high-temperature streams were integrated with a supercritical power plant in previous works [18,20] where the value of the operational variables which improve overall system efficiency and cost are defined.

Plant operation parameters represent the keys for increasing the efficiency and the economic benefits of a plant. Linnhoff and Flower [21,22], Linnhoff [23] and Linnhoff and Hindmarsh [24] introduced the concept of heat integration by developing the pinch method, which has been extensively applied in many industrial saving energy problems [25–32]. The objective of heat integration is to reduce the external energy requirements of the process (known as utilities) by increasing the energy recovery between the hot streams (HS) and the cold streams (CS) involved in the process. The pinch method is used to identify the best possible degree of heat recovery as a function of the minimum temperature difference in the heat exchangers, ΔT_{min}. The amount of heat that can be transferred between the hot and cold streams in the system and the minimum energy requirements – (MER), external heating or cooling needs that should be supplied to the system – are determined by applying this method.

Once the pinch methodology has been applied and MER has been calculated, the next step is to choose the most suitable HEN among those which satisfy the MER. In this work, a multi-criteria comparison is carried out, taking into account energy, economic and exergy analyses. Four different configurations with the same MER are proposed for the integration of a Ca-looping CO_2 capture system with a supercritical steam cycle. Calculations enable to compare and select the more appropriate network to meet the selected criteria.

2. Global system description and modelling

The calcium looping cycle, the CO_2 compression train and the supercritical steam cycle form the global system under study. A 500 MW (gross) power plant fed with high-rank coal (0.6% sulphur content), with a net efficiency of 38.23% LHV supplies the Ca-looping CO_2 capture system with its flue gas (546.8 kg/s, 14.81% CO_2 content).

Table 1
Main technical assumptions of the global system.

Carbonation/calcination system		
Purge percentage	(%)	2.5
Purge final T	(°C)	180
Ratio CaO/CO_2		5
Carbonation final flue gas T	(°C)	180
Calciner flue gas T before compression	(°C)	50
Recirculated CO_2 from calciner FG	(%)	20.1
ASU consumption	(kW h/tCO_2)	220
CO_2 compression train		
Intercooling T	(°C)	50
Pressure ratio at CO_2 compression		3.3
Turbocompressors isentropic efficiency	(%)	80
Supercritical steam cycle		
Deareator pressure	(bar)	7
Condenser pressure	(bar)	0.042
Live steam properties at turbine inlet	(°C)	600
	(bar)	290
Reheat steam properties at turbine inlet	(°C)	620
	(bar)	48.5

High-temperature heat flows from Ca-looping cycle (carbonation reaction heat, gases leaving both carbonator and calciner and solids purge stream) were included to design the high-pressure equipment of the supercritical steam cycle (heat recovery steam generator, reboiler and high-pressure pre-heaters) according to the heat exchangers temperature levels [20]. Low-temperature streams from the CO_2 intercooling compression train were used in the low-pressure section of the steam cycle, avoiding turbine bleeds, which diminish power production. The main technical assumptions of the global system can be found in Table 1.

Different sets of equations were incorporated into the capture cycle modelled with Engineering Equation Solver (EES) to define CaO capture capacity integrating relevant phenomena [18,33,34]. While the heat exchanger network was kept constant in previous studies [18,20], the comparison of different heat exchanger networks (HEN) which improve the initial one according to energy, economic and exergetic criteria, constitutes the main novelty of this work.

Fig. 2 illustrates the flowsheet diagram of the heat integration proposed by Lisbona et al. [18]; in which available heat flows from the CO_2 capture system and the CO_2 compression train (CT) are used to define a supercritical power plant. This HEN [18,20]consisted of 18 heat exchangers, distributed according to temperature restrictions, to keep a minimum difference of 20 °C between their hot and cold sides; and is considered the base case (BC) for this study. The pinch method was applied to improve the initial heat exchanger network assuming the same minimum temperature difference than in BC, 20 °C.

The energy and mass balances closure of the base case define a set of hot and cold streams, see Table 2. Hot streams are those which have to lower their temperature while cold streams need to rise theirs. Streams listed S-1 to S-7 define the capture process; streams S-11 to S-16, the CO_2 compression train and S-20 to S-23 the supercritical steam cycle. Stream S-1 represents the heat that must be evacuated from the carbonator reactor, and stream S-11 is the condensation heat of the CO_2 and H_2O mixture before the compression train; both are defined as latent heat. Total amount of heat, temperature range, heat capacity flowrate (CP), mass flow and exergy of every stream are specified in Table 2, and shown in Fig. 2.

Fig. 3 shows simultaneously the Grand Composite Curve (GCC) corresponding to capture cycle plus CO_2 compression processes (bold line, 1005.07 MW of cooling needs) and the GCC of the global system (grey dashed line, 71.75 MW of cooling needs) composed