Fuel 127 (2014) 4–12

Contents lists available at ScienceDirect

Fuel

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

A systematic approach for high temperature looping cycles integration

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HIGHLIGHTS

- A procedure for integrating high temperature CO_2 capture systems is developed.
- Two sorption–desorption cycles for CO_2 capture are assessed applying this methodology.
- The most economical HEN for each case was obtained by following the procedure.

ARTICLE INFO

Article history:
Received 31 May 2013
Received in revised form 22 August 2013
Accepted 18 September 2013
Available online 1 October 2013

Keywords:
CO_2 capture
Ca-looping
Energy integration

ABSTRACT

High temperature solid cycles are promising technologies for implementing large-scale CO_2 capture facilities in the mid-term. Energy integration plays a major role in the development of these cycles. Waste energy from the capture process may be used to retrofit an existing power plant or to power a new steam cycle, thus diminishing the energy penalty that the process entails. A procedure based on pinch analysis for the integration of these systems, is proposed and tested using limestone as CO_2 sorbent. Although Li_4SiO_4 has been already dismissed for this purpose, it is used to validate the systematic procedure under a very different problem in terms of available heat and initial temperatures of hot streams. In both scenarios the integration was designed to take advantage of all available heat of the process and to power a supercritical steam cycle, quantifying their minimum energy penalty. A sensitivity analysis for each process was also developed, and the heat exchanger network achieved by the proposed algorithm obtained the best results in costs terms.

1. Introduction

The IPCC identified carbon capture and storage from large CO_2 sources as a feasible measure for short and mid-term climate change mitigation [1]. There exist several capture techniques classified depending on the location of the separation stage in the utilization chain of the fuel. Among post-combustion processes, high temperature sorption–desorption cycles appear to have great potential [2,3]. These processes are based in the use of solid sorbents to remove CO_2 from a mixture of gases.

The flue gas from a power plant feeds a first reactor where the CO_2 contained in this stream reacts with the active sorbent to form a new compound. In a second step, the carbonated compound is circulated to a calciner where sorbent regenerates, producing a concentrated stream of CO_2 suitable for transport and compression. Calcination step will occur at higher temperatures than sorption step. Heat requirements for sorbent calcination are covered by oxyfuel combustion of coal in the second reactor itself. Once regenerated, the sorbent returns to the first reactor to begin a new sorption cycle.

Natural and synthetic solid sorbents may be used [4,5]. Each compound carbonates and calcines at different temperatures, depending on its equilibrium constant. One critical aspect of sorption–desorption capture processes deals with conversion efficiency of capture reaction under process conditions and its variation after several cycles [6,7]. Deactivation of the sorbent carbonation with an increasing number of cycles is a key parameter that influences on both cost and heat requirements. To compensate for these losses in sorbent activity, a make-up flow of fresh sorbent is introduced in the calciner and a controlled purge flow of deactivated material close the mass balance in the reactor.

As any other capture technology, energy consumptions in the capture cycle penalize by several percentage points the energy efficiency of the power plant. The heat demanded for regeneration covers a large fraction of the overall amount of energy in the system [8]. The capture process operates at relatively high temperatures and presents a great potential for energy integration.

Energy integration plays an important role in the development of this technology and may limit the energy penalty to 10–12 efficiency points [9]. A great share of the energy input may be recuperated from the hot gas and solid streams leaving the system. The

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0016-2361/$ - see front matter © 2013 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.fuel.2013.09.062

heat released by the exothermic carbonation reaction that must be evacuated to control operating temperature is also available for integration. Low-grade heat may be recuperated from the CO_2 intercoolers included in the compression stage required for conditioning CO_2 for transport and storage. This energy may be used to retrofit an existing power plant [10,11] or to power a new steam cycle [12,13].

A systematic procedure for heat integration of this type of systems is proposed to find an energy and cost-efficient solution for the heat exchanger network (HEN). In Section 2, the sequential steps of the proposed algorithm are detailed. This procedure is applied to define the heat exchanger networks for two different cases. The first option assesses the HEN obtained when CaO sorbent is used (Section 3) and the other one analyses the resulting HEN using Li_4SiO_4 as CO_2 sorbent to validate the procedure (Section 4). In both scenarios, the energy integration was designed to take advantage of all available heat streams from the capture process into a supercritical steam cycle. A sensitivity analysis of several HEN configurations is performed to assess the suitability of the new procedure in terms of energy and costs (Section 5).

2. HEN definition procedure

The main objective of this study is to design a procedure to systematically develop a heat exchange network that covers the heating needs of every cold stream in the global system just by exhausting the available energy streams from the capture process. The pinch methodology is a widely applied technique used to define the hot and cold streams of a system and obtain their minimum energy requirements (MER). It establishes a set of rules to build the heat exchanger network that accomplishes the energy target [14].

This work presents a procedure that proposes an specific order to determine the matches between streams according to the pinch method. This approach leads to a single heat exchanger network suitable for threshold problems with high cooling MER, as the integration problems presented for high temperature looping cycles.

The proposed algorithm follows the structure shown in Fig. 1. First, the energy streams must be ranked in descending order; hot streams according to their inlet temperature; and cold ones according to their objective temperature.

The cold stream in top of the list (the one with the highest objective temperature) is selected and associated to variable *C*. This variable is the input to a subprocedure, *Match (C)*, which assesses the possibilities of the cold stream to exchange heat with the hot streams in the system. The prioritized matching criteria is the exhaustion of any of the selected streams in a single heat exchange, i.e. the hot stream totally transfers its available energy content or the heating needs of the cold stream are completely fulfilled. Two restrictions are imposed for the heat exchanger definition:

- Initial and final temperatures of the hot stream must exceed the cold stream temperature by a minimum ΔT_{pinch} to avoid temperature-crossing during the heat exchange.
- A minimum increase of the cold stream temperature of $\Delta T_{pinch}/2$ is required to consider the heat exchange efficient enough.

The first step in *Match (C)* subprocedure is to check whether any hot stream may exhaust cold stream *C*. If this condition is achieved, both streams exchange heat and the new inlet temperature and available heat of the hot stream are calculated. If more than one hot stream fulfill the restrictions, that one with higher initial temperature is selected to match the current *C* (the cold stream with highest objective temperature). The outputs of this block are released as data for the general process and *C* is marked as exhausted.

In case that no single hot stream can exhaust stream *C*, two different exchange options are checked: the potentiality of stream *C* to exhaust any hot stream (case A) and the possibility of exhausting stream *C* by means of the addition of several hot streams (case B). In this last scenario, stream *C* is divided in parallel streams, that will sequentially exhaust the chosen hot streams until every *C* substream is also exhausted. A and B are simultaneously examined and four different situations may appear (see Fig. 1):

(i) Only A is possible. The corresponding heat exchange is calculated, the selected hot stream is marked as exhausted and the new objective temperature and remaining energy needs of stream *C* are obtained. The hot stream with the highest heat capacity flowrate (CP) is chosen if several hot streams fulfill this condition.

(ii) Only B is possible. Stream *C* is divided in parallel substreams and the corresponding heat exchanges are calculated. The hot streams are exhausted with the corresponding cold sub-streams. In case the last hot stream involved in the heat exchange is not exhausted, its temperature and energy content are accounted as new data for the global process. Again, hot streams are chosen prioritizing those with the highest CP.

(iii) Nor A neither B conditions are possible. Under this scenario, there are no options to exhaust a stream in a single heat exchange and they must be partitioned. Stream *C* will exchange heat with the hot stream with the highest CP, until their temperature difference in the cold side equals the ΔT_{pinch} limiting value.

(iv) A and B conditions are possible. The stream is marked as an special case and both configurations, B and A, are examined. The heat exchangers are calculated for both scenarios and case A is a priori implemented. Case B results (temperatures and energy needs) are saved and used for comparison in the general procedure.

The data obtained from *Match (C)* subprocess are introduced into the general procedure. If *C* is not exhausted, the streams are ranked again according to their new temperature values and the loop continues. Once *C* is exhausted, it must be checked whether this stream was classified as an special case within *Match (C)* or not. In case *C* is not marked as special, the streams are ranked and the process continues choosing a new stream as *C*. Otherwise, there would exist two possible HEN designs for this stream. Both designs are compared and the configuration with a lower number of heat exchangers is chosen as the final design for *C*. Once this step is completed, the loop continues. The HEN is totally defined when there are no cold streams left.

This procedure was applied to a cyclic CO_2capture process using two different sorbents: calcium-looping CO_2 capture is detailed in Section 3, and sorption–desorption using Li_4SiO_4 is proposed and its HEN configuration developed in Section 4. Each case presents different temperature levels and available energy content. For both, the performance of the procedure has been analyzed by developing and comparing with alternative HENs; Section 5.

3. CaO–$CaCO_3$ cycle

Calcium based sorbents are widely investigated since they present some advantages such as the relatively low cost of the sorbent, the absence of flue gas pretreatment or the possibility of integration with cement industry [15]. The capture process follows reaction (1).

$$CaO + CO_2 \rightleftharpoons CaCO_3 + Q \quad (1)$$