Powder Technology 253 (2014) 116–128

Contents lists available at ScienceDirect

Powder Technology

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

Cold model hydrodynamic studies of a 200 kW_{th} dual fluidized bed pilot plant of calcium looping process for CO_2 Capture

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ARTICLE INFO

Article history:
Received 1 August 2013
Received in revised form 21 October 2013
Accepted 23 October 2013
Available online 9 November 2013

Keywords:
Calcium looping
CaL
CO_2 capture
Dual fluidized bed (DFB)
Cold model

ABSTRACT

The calcium looping (CaL) process is a post combustion CO_2 capture technology which is currently under development, offering power plants a low cost and energy efficient solution for carbon capture. At IFK, University of Stuttgart, a 200 kW_{th} CaL dual fluidized bed (DFB) pilot plant has been built consisting of two circulating fluidized bed (CFB) reactors. This study presents detailed results of tests conducted on a hydrodynamically scaled cold model of the 200 kW_{th} CaL DFB facility. The preliminary aim of the cold model studies was to check the workability of the major novelty of this facility which is the implementation of two cone valves to control the solid looping rate between the two CFBs. Furthermore, initial cold model tests, based on the relative CaL process boundary conditions, determined the suitability of the 200 kW_{th} CaL DFB system and further tests suggested design improvements for the pilot plant. The novel geometric configurations in a CFB such as a wide bottom CFB reactor and a loop seal with increased weir depth were tested and found to be a useful application for the pilot plant operation. All important process parameters of the cold model DFB system, namely total solid inventory (TSI), riser superficial velocity, air staging ratio, and cone valve opening, were varied in order to fully characterize the DFB operation. The study shows that the proposed solid looping mechanism works satisfactorily and the required operational boundary conditions can be met in the pilot plant with suggested design improvements.

1. Introduction

Increased consumption of fossil fuels has caused increment in the concentration of greenhouse gases in the atmosphere which is threatening a serious global warming and climate change [1]. CO_2 is a major contributor to global warming and drastic emission reduction in the atmosphere is a necessity of the present. Nearly 1/3rd of the global CO_2 emissions come from coal and natural gas fired power plants [2] and future energy trends do not show any reduction in consumption of these fuels [3]. An interim approach, till the world makes a switchover from carbon/fossil based fuels to sustainable renewable sources, is carbon capture and storage (CCS). Various carbon capture methods have been suggested. Amine scrubbing and oxyfuel combustion are currently being the most developed technologies, applied with a plant capacity up to 30 MW_{el} [4] and 40 MW_{th} [5] respectively. However these processes are facing challenges of efficiency loss and economics [6]. The calcium looping process (CaL) provides a solution for the lower efficiency loss and better economics [6].

1.1. The calcium looping process

The calcium looping (CaL) process is a promising post combustion CO_2 capture technology which utilizes CaO as CO_2 sorbent in a dual fluidized bed (DFB) system. This process is first suggested by Shimizu et al. [7] and is based on the carbonation–calcination reverse reaction of limestone shown in Eq. (1).

$$CO_2 + CaO \rightarrow CaCO_3 (\Delta H_R = \pm 172.5\ kJ/mol). \quad (1)$$

The block diagram of the CaL, illustrated in Fig. 1, consists of two reactors a carbonator and a regenerator. In the carbonator, power plant flue gases containing CO_2 enter the reactor operated at 600–700 °C and the carbonation reaction takes place to form $CaCO_3$ as per the above exothermic reaction of Eq. (1). The CO_2 lean flue gases leave the carbonator and the formed solid $CaCO_3$ is transferred to the regenerator where at 900–950 °C the reverse endothermic reaction of Eq. (1) takes place and $CaCO_3$ is converted into CaO with simultaneous CO_2 release. The regeneration step requires energy for the endothermic reaction which is provided through the oxyfuel combustion of additional carbonaceous fuel. The regenerated CaO is returned to the carbonator for subsequent CO_2 capture. With continuous carbonation calcination cycles, the sorbent undergoes deactivation and loses its reactivity [8], furthermore continual usage also causes losses due to the mechanical damage of the limestone particles, therefore a fresh sorbent make-up flow is necessary.

The calcium looping process offers several advantages compared to other CO_2 capture technologies. The main advantage is the high temperature level in both reactors; which enables additional steam generation through the heat released in the carbonator and flue gas streams.

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0032-5910/$ – see front matter
http://dx.doi.org/10.1016/j.powtec.2013.10.043

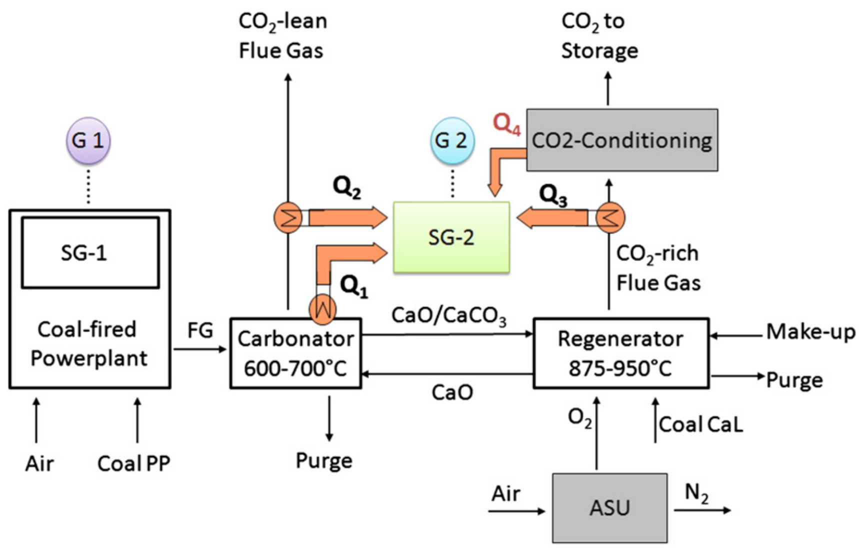

Fig. 1. Integrated scheme of calcium looping process. (ASU — Air separation unit, FG — Flue gases, SG — Steam generator, Q = heat sources).

Therefore, with a calcium looping plant the power output of the source power plant increases by about 40% while the reduction in overall efficiency of the entire power plant only accounts for 3–8% [9,10] which is moderate compared to other CO_2 capture technologies such as oxyfuel and amine scrubbing.

Ever since the conceptualization [7], the CaL process has been developed steadily. This involved microscaled TGA studies for understanding sorbent behavior, economic analysis [6,11], simulation studies [9,12–15], lab scale demonstrations [16–19] till the successful demonstrations at pilot scaled plants [20–23]. At present three pilot scale plants are currently under investigation. IFK, University of Stuttgart 200 kW_{th} pilot plant has been in operation since 2010 [20,24]. This paper mainly focuses on the hydrodynamic feasibility studies of this 200 kW_{th} plant at IFK, performed on the scaled cold model during the design phase. Other pilot scale plants are the 1.7 MW_{th} by Endesa in Spain [22,25] and the 1 MW_{th} at TU Darmstadt, Germany [23]. At ITRI, Taiwan 1.9 MW_{th} pilot plant is recently commissioned [26].

1.2. The 200 kW_{th} dual fluidized bed pilot plant for CaL at IFK

The dual fluidized bed (DFB) reactor system is a preferred reactor system for the calcium looping process. A DFB system is a combination of two fluidized bed reactors with an interlinking between the two fluidized beds for solid transport. The DFB systems offer a convenient transport of the solid reactants from one reactor to the other without mixing the gases between the two reactors. Processes such as chemical looping combustion (CLC) and sorption enhanced reforming (SER) also utilize DFB systems [27]. Together with calcium looping SER and CLC are grouped as high temperature solid looping cycles [28].

The 200 kW_{th} CaL pilot plant at IFK, University of Stuttgart is a CFB–CFB type DFB system. The schematic of the 200 kW_{th} pilot plant is shown in Fig. 2. The details of the complete plant can be referred in Hawthorne et al. [24]. The basic scheme consists of a carbonator and a regenerator which are both circulating fluidized bed (CFB) reactors. In previous studies [18,19,29], it is found that the CFB carbonator is more effective than the BFB reactor in terms of the equal space time requirement. In BFB reactor the gases can bypass the solid reactants without reaction through bubbles. In CFB reactors the gas solid contact is qualitatively better. Therefore a CFB is selected for the carbonator. In the regenerator the heat required for the regeneration step of Eq. (1) is generated by the combustion of carbonaceous fuels. A CFB is well proven commercially for its application as a combustor [30]. Therefore, the regenerator is also selected as a CFB. Each CFB consists of a riser–cyclone–standpipe–loop seal and a return leg arrangement, which is typical for a standalone CFB unit. The interlinking of the fluidized bed is very important in DFB systems to transport solid particles without mixing gases between the two fluidized beds. Various types of interlinking are in use such as loop seals, double exit loop seals [27], L-valves [31] and pneumatic transport [16]. In the 200 kW_{th} pilot plant the two CFBs are connected by two separate cone valves which are situated at the bottom of the loop seal of each CFB as shown in Fig. 2. A cone valve is a mechanical valve which is also used in commercial CFB boilers for transferring bed material to the external heat exchangers [32]. The cone valve has also been previously used at IFK, University Stuttgart for the CaL process [18,19,33] for controlling solid looping rates. The control of the solid looping rate is important in CaL process for two main reasons. First, the control of solid looping rates allows more flexibility in terms of carbonator flue gas loading. Secondly due to the degradation of sorbent reactivity [8], which is a major concern for CaL, the highly reactive sorbent requires lower solid looping rate while low reactive sorbent requires high solid looping rate. Therefore as per the sorbent reactivity, the solid looping rate should be varied to keep the desired level of CO_2 capture efficiency.

DFB systems consisting of two CFBs have been used previously [10,23]. Although the use of two CFBs is similar to the pilot plant design (Fig. 2), the mechanism of solid looping between the reactors is different. Considering the novelty, the size and the investment of the pilot plant depicted in Fig. 2, the hydrodynamically scaled cold model studies will be proved useful in providing the data related to the feasibility of the concept and the design. The preliminary results of the cold model investigation have been shown in Bidwe et al. [35]. The present study gives much detailed study about the cold model investigations while the preliminary results of Ref. [35] were limited to discussion about the hydrodynamics of the carbonator and regenerator in a single loop operation and air staging influence in the regenerator. Based on the present cold model study the pilot plant has been constructed and commissioned [36]. The pilot plant has shown promising results of the CO_2 capture [20].

1.3. Gas solid transport in the 200 kW_{th} pilot plant

In the pilot plant operation the flue gases enter the carbonator. In the carbonator, CO_2 is absorbed by the active CaO at the temperatures between 600 and 700 °C to form $CaCO_3$. The CO_2 lean flue gases and the formed $CaCO_3$ leave the carbonator and enter the cyclone (cyc_{Ca}), where gas solid separation takes place. The gases leave the cyclone from the top exit while the solid $CaCO_3$ particles drop into the standpipe (stp_{Ca}). The solid flow rate of $CaCO_3$ particles falling in standpipe is called entrainment rate (G_{Ca}) in kg/h or entrainment flux ($G_{S\,Ca}$) in kg/m^{2}s. Part of this