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Development of a dual conical spouted bed system for heat integration purposes

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ABSTRACT

This paper describes preliminary studies carried out to develop a system made up of two interconnected spouted beds for heat integration in highly endothermic processes, such as pyrolysis and gasification. Four different configurations of a dual spouted bed system have been studied depending on the location of the feeding and discharging points in the interconnection pipes, i.e., annulus–annulus, annulus–spout, fountain–spout and fountain–annulus. Fountain–annulus configuration has been determined to be the optimum option based on its stability, solid transfer rate (around 120 kg h^{-1}) and gas bypassing from one contactor to the other (below 1.5%). Once the optimum system has been established, the viability of the dual spouted bed system has been assessed for heat integration in the biomass pyrolysis, with the minimum temperature difference between the pyrolyser and combustor being 280 °C for attaining allothermal operation. Furthermore, studies have been carried out on the solid circulation rate (energy balance), gas bypassing from one contactor to the other and system stability against different perturbations, which have allowed determining the optimum configuration.

1. Introduction

The spouted bed is a fluid–particle contact technique that has been successfully applied to systems where fluidization has yielded unsatisfactory results, especially for coarse materials [1]. The main advantages over the fluidized bed are related to its well-defined cyclic movement of the particles, facilitating excellent contact between the gas and solid particles [2]. In fact, the high solid circulation rate and efficient gas–solid contact allow the application of this technology in many chemical processes [3].

In the spouted beds, the fluid introduced through a central nozzle forms a jet and causes the particles to circulate in a uniform way creating a central spout zone. The fluid and particles are in counter-current flow in the annulus, which makes up the major portion of the spouted bed. Particle flow is co-current in the spout, where velocities are high and residence times short. The excellent gas–solid contact and high heat transfer rates in spouted beds make them suitable for physical processes, such as drying [4–6] and coating [7–9], and chemical processes, such as pyrolysis [10–14], gasification [15–18], reforming [19,20] and combustion [21,22].

However, heat transfer limitations through the wall arise for highly endothermic applications, such as steam gasification and pyrolysis, and especially for large scale applications. Thus, as the process is being scaled up, the external surface of the reactor by volume unit decreases, and therefore the ratio between the heat required in the process and the reactor external surface area increases. Accordingly, an alternative heat integration strategy must be developed for scaling up highly endothermic processes. The heat integration scheme proposed here is based on two interconnected spouted beds, i.e., the endothermic process (pyrolysis or gasification) takes place in one of the reactors and the exothermic one (combustion) in the other. The energy for the endothermic step is provided by the bed material in the exothermic process unit. The material burnt is the char formed in the pyrolysis/gasification process, although additional fuel may also be used, depending on the energy requirements of the endothermic process [23].

Different heat integration systems using the energy contained in the char have been developed for biomass pyrolysis processes. Thus, Janse et al. [24] propose an original reactor of laboratory scale made up of a rotating cone reactor immersed in a fluidised bed combustor. Boukis et al. [23] developed an air blown pyrolyser made up of a riser in which pyrolysis takes place, and a fluidised bed in which char is burnt. The reactor developed by Zhang et al. [25] (internally interconnected fluidized bed) solved the heat transfer from the combustor to the pyrolyser by means of a dipleg for inert material circulation. Similar systems based on two interconnected fluidized beds have been applied in the steam gasification of biomass. Thus, the dual fluidised bed technology has been successfully scaled up [26–28]. Zhang et al. [29] published a review devoted to the application of dual fluidised beds to gasification and pyrolysis processes. Regarding the studies carried out in the literature using interconnected spouted beds, to our knowledge there are only two previous experiences. Tamm et al. [30] patented a similar system

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to that studied here; that is, the solid was collected in the annular region of one spouted bed and conveyed to the gas inlet of the other. Paterson et al. [31] developed a more sophisticated system including a riser to exchange solid between spouted bed contactors.

The aim of this paper is to develop a novel system made up of two interconnected spouted beds with continuous solid circulation from one contactor to the other. This dual spouted bed system is especially interesting for heat integration in highly endothermic processes, such as large scale pyrolysis and gasification. The dual spouted bed system facilitates heat transfer from exothermic processes (combustion) to endothermic ones (pyrolysis or gasification) based on the solid circulation from one reactor to the other, with their operating temperatures being different. Different configurations are proposed and an optimization study is carried out by considering system stability, solid circulation between the spouted beds and gas bypassing.

2. Material and methods

2.1. Experimental setup

The experimental setup is made up of two conical spouted bed contactors of the same geometry and dimensions. The contactors are made of stainless steel (AISI 304) and are provided with three small windows, one in the conical section and the other two in the cylindrical one, for visual observation of the solid circulation in the bed. The dimensions of the contactors used in this study are the same as those of the pyrolysis pilot plant built in Ikerlan-IK4 [32–34]. The main dimensions are shown in Fig. 1 and are as follows: an upper diameter (D_c) of 242 mm, a conical base angle (γ) of 32°, a cone height (H_c) of 330 mm and a total height of 1030 mm. The base diameter is (D_i) 52 mm. In order to improve the stability of the spouting regime in a wide range of operating conditions, a draft tube has been inserted in the contactors [2,3,5,35,36]. This device improves the versatility of the contactor, i.e., a change in the height of the entrainment zone modifies the solid circulation rate [2,37,38]. The inlet conduit is a part with a flanged joint prepared for a mesh to be fitted for supporting the bed and fixing the draft tube. The inlet diameter (D_0) is 25 mm. The draft tube internal diameter (D_T) is 36 mm and the entrainment height (L_H) is 80 mm. The tube height is equal to that of the stagnant bed height; that is, from 270 mm in the runs with 6 kg of sand in the bed to 360 mm in those with 12 kg of sand. The selection of the draft tube and the optimization of the pyrolysis reactor performance under ambient conditions have been approached in a previous paper [33]. The interconnection tubes are made of transparent material in order to allow visual observation of the solid circulation pattern between the contactors. Two types of tubes have been used, non-flexible ones made of PMMA and flexible corrugated pipes of PVC. All the experiments have been carried out at ambient temperature.

The fluidizing gas used in both contactors is air (mixed with a small fraction of nitrogen when gas bypassing is studied) and is provided by means of a rotary piston blower, whose flow rate is measured using a mass flow gauge (Brooks, 5853S). A ball valve is placed at the outlet of both spouted beds to vary the pressure inside the contactor and allow studying the effect pressure fluctuations have on system stability. The pressure at the contactor inlet and outlet was measured using pressure transducers (STW C01). The pressure drop and the air flow rate were monitored and recorded by a Fluke Netdaq Logger data collection system. The frequency for pressure drop monitoring was 6 readings per second.

The study has been performed using commercial A-GR207 silica sand supplied by *Minerales Sibelco*. The main properties of this material are: density, $\rho_s = 2600$ kg/m^3, static bed voidage, $\varepsilon = 0.46$, sphericity, $\Phi_s = 0.86$ and minimum fluidization velocity, $u_{mf} = 0.42$ m/s. The particle size distribution of the sand determined by sieving is between 0.06 and 2 mm and the Sauter mean diameter (or reciprocal mean diameter) is $d_s = 1.05$ mm.

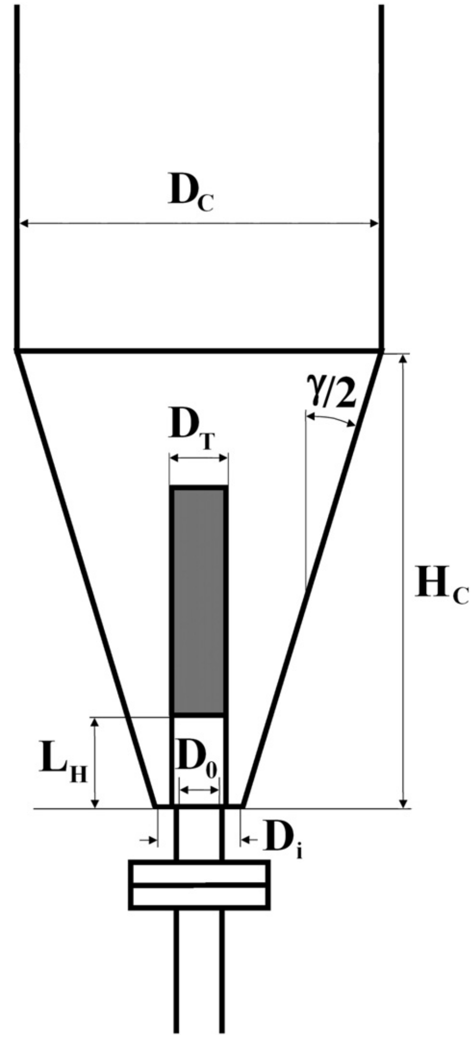

Fig. 1. Geometric factors of the spouted bed contactors.

A series of preliminary runs have been carried out with the aim of attaining a basic knowledge of the performance of the two spouted bed interconnected system. Thus, four different configurations have been studied for the interconnection between the beds, depending on the location of the solid inlet to the transfer pipe in one bed and the solid discharge in the other, which are as follows: annulus–annulus, annulus–spout, fountain–spout and fountain–annulus. Fig. 2a, b, c and d shows these four different dual spouted bed configurations.

Preliminary runs evidenced that the solid flow rates collected in the fountain are very low due to the dilution of the fountain and the small pipe inlet section. Accordingly, a plate was designed for collecting the solid in the fountain and feeding it into the interconnecting pipe joint at the lower end of the plate. A suitable design of this plate is essential for allowing flexibility in solid flow rate. Fig. 3 shows the location and design of the plate in the spouted bed. The plate covers the whole cross-section of the contactor, except a central hole with a short pipe (a few centimeters length), which allows particles rising above the plate and falling down onto its surface. The short pipe is required to avoid solid falling down again onto the bed surface. The plate has been inserted at a height of 10 cm above the cone–cylinder junction (measured at the axis of the bed), which is approximately half of the fountain height for most of the runs carried out.

The influence of the internal diameter of the interconnection pipes has been studied by using pipes with diameters from 18 to 50 mm. Pipe inclination is another crucial feature influencing solid transfer. Accordingly, this parameter has been varied in a wide range in the