Fuel 203 (2017) 825–831

Contents lists available at ScienceDirect

Fuel

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

Full Length Article

Assessment of a conical spouted with an enhanced fountain bed for biomass gasification

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HIGHLIGHTS

- Fountain enhanced spouting regime was developed for biomass gasification.
- The aim is to increase residence time and gas-solid contact in the fountain region.
- This regime is stable operating with fine materials and high gas velocities.
- Temperature has a remarkable effect on fountain enhanced spouting velocity.
- Several parameters may be fine tuned in order to meet the most suitable conditions.

ARTICLE INFO

Article history:
Received 13 March 2017
Received in revised form 3 May 2017
Accepted 4 May 2017
Available online 17 May 2017

Keywords:
Conical spouted bed
Hydrodynamics
Fountain confinement
Biomass gasification

ABSTRACT

This study pursues the development and characterization of a fountain enhanced spouting regime. This novel gas solid-contact method combines the advantages of fountain confined conical spouted beds with those of draft tube conical spouted beds. The aim of confining the fountain, and therefore attaining a clearly differentiated regime, is to progress towards a highly efficient conical spouted bed reactor for biomass gasification. Accordingly, and in order to delve into the knowledge of the regimes attained in this contact method, a study has been conducted by analyzing the influence operating parameters (temperature, gas flow rate, particle size and bed mass) and draft tube geometry (tube diameter and entrainment zone height) have on hydrodynamics. Fountain confinement allows greatly enlarging the fountain region, especially the height, which improves the contact between reacting gases and the catalyst. Moreover, the residence time distribution, and therefore the average residence time, may be optimized by confining and enlarging the fountain zone. These features promote tar cracking and so increase biomass conversion efficiency, which are highly relevant facts for use of conical spouted bed reactors in gasification.

1. Introduction

The spouted bed is an alternative fluid-particle contact method to fluidized beds, which has been successfully applied to systems in which conventional fluidization has yielded unsatisfactory results, especially when coarse materials are handled [1]. The main features of this technology are related to the well-defined cyclic movement of the particles, which allow for an excellent contact between the gas and solid particles, promoting high heat and mass transfer rates. This original fluid-particle contact makes spouted beds suitable for many industrial applications, such as drying [2,3], coating [4,5], pyrolysis [6,7] and gasification [8–10]. Furthermore, several modifications of the original one reported by Mathur and Gishler [11] have been proposed in order to increase the applicability range, as are two dimensional spouted beds [12–14] and spout fluid beds [15–17].

Thus, the aim of this paper is to develop a novel gas-solid contact regime based on a conical spouted bed reactor for the optimization of its performance in biomass gasification. The conventional conical spouted bed is characterized by its short residence time, which is an excellent feature for minimizing undesired secondary reactions in pyrolysis processes [6,18]. Nevertheless, it is a serious drawback for gasification, as short residence times hinder tar cracking reactions [8,19,20].

When designing gasifiers a critical point to consider is process efficiency in terms of gas composition and, especially, avoidance of tar formation [21]. According to Bridgwater [22], there are three main design aspects of special significance for improving reactor performance: i) Additional residence time after the gasification step, ii) Direct contact with high temperature surfaces and iii)

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http://dx.doi.org/10.1016/j.fuel.2017.05.014
0016-2361/

Partial oxidation by injecting air or pure O_2. Several attempts have been carried out to fulfil these objectives, and secondary air injection in the freeboard region of fluidized bed gasifiers has been reported as a suitable method to reduce tar content because it increases temperature in this region [23,24]. Another strategy used for enhancing tar cracking is the separation of pyrolysis and reduction zones in the gasifier [25,26].

The modifications proposed in this study for the conical spouted bed reactor pursue two of the guidelines proposed by Bridgwater [22], i.e., residence time increase and additional direct contact with heat carrier particles in the bed fountain. The most significant modification lies in the fountain confinement, which has been performed by welding a tube to the lid of the reactor, with the lower end of the tube being close to the surface of the bed (Fig. 1). This device was originally designed with the aim of handling fine materials by retaining the particles in the fountain region, and therefore avoiding their entrainment from the bed [27]. In addition, this system greatly contributes to the stability of the spouting regime and gas flow distribution in the reactor, with hardly any effect on pressure drop. To the authors' knowledge, the single previous reference of a device with certain similarity to the one developed here is the side-outlet spouted bed developed by Hattori et al. [28,29]. However, the aim of this configuration was not fine particle retention, but process scaling-up.

Fountain confined conical spouted beds allow operating with finer catalyst particles than conventional conical spouted beds, and therefore the gas flow rate for spouting is much lower. This point is of great significance, since it allows increasing residence time, and therefore promoting tar cracking [21,30]. Moreover, it also eases the adjustment of steam/biomass (S/B) ratio (or ER in the air gasification process) because the gasification agent also acts as fluidizing agent. This fact is of special significance, given that S/B ratio is a key parameter for process performance optimization [31]. The longer residence time of the gas phase is attained by increasing the reactor volume, i.e., longer cylindrical section and fountain region height. A simple similar solution has been successfully applied to improve the performance of a fluidised bed gasifier by increasing the height of the freeboard region [30].

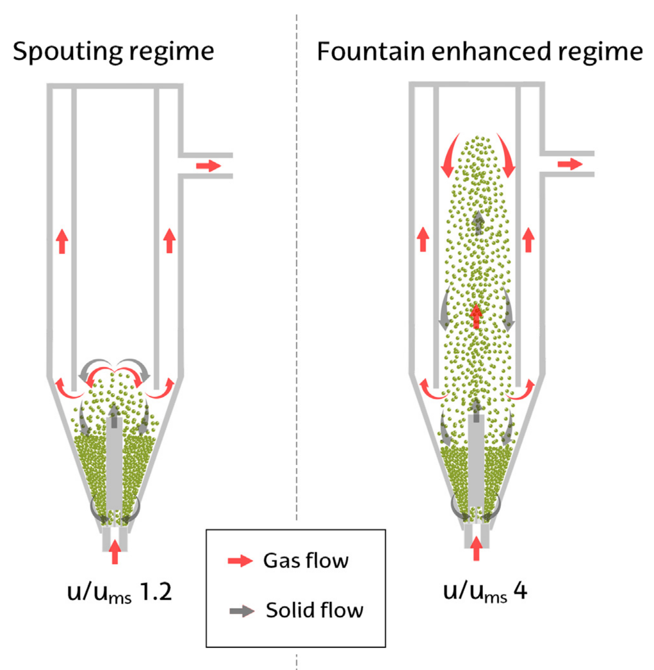

Fig. 1. Schemes of the conventional spouting and the fountain enhanced regimes.

Furthermore, this device for confining the fountain also allows for modifying the residence time distribution. Thus, it avoids the direct release of the biomass derived gases from the reactor since it forces the gas to circulate through the confined fountain region. Therefore, the novel gas-solid contact regime developed in this study is based on the fountain confined conical spouted bed. The fountain enhanced spouting regime is attained by using a gas velocity four times the minimum spouting one. This regime is characterized by a severe expansion of the bed (in the fountain) and high turbulence. Fig. 1 shows a scheme of the contactor operating with a gas velocity slightly above the minimum one and with a gas velocity corresponding to the fountain enhanced regime, which is approximately four times the minimum one when operating with fine materials, and higher when operating with coarse materials. The conditions in the latter promote contact between tar compounds in the gas phase and catalyst particles, which is essential to ensure tar elimination [32].

The use of a non-porous draft tube has also been considered for the optimization of the fountain enhanced regime as it allows for operating with low gas flow rates for attaining high residence times [12,33–37]. In fact, the non-porous draft tube promotes high fountains [37,38] by diverting most of the inlet gas stream through the draft tube, which enhances particle dragging, and therefore leads to additional gas-solid contact in the fountain.

2. Material and methods

2.1. Experimental set-up

The experimental runs were conducted in a stainless steel conical spouted bed reactor designed for the pyrolysis [6,18,39] and gasification [8,10] of different solid wastes. The reactor is provided with a fountain confiner welded to the lid in order to increase the residence time, narrow its distribution and improve the gas-solid contact in the fountain region. This reactor may also operate in the conventional spouting regime by using a lid without confiner. Moreover, draft tubes of different configuration may also be used to widen the application range of the spouting regime and improve bed stability [33,34,37]. Thus, three non-porous draft tubes of different geometry have been tested in this paper. The main dimensions of the reactor are shown in Fig. 2, and are as follows: cylindrical section diameter 95 mm, height of the conical section 150 mm, cone included angle 30°, length of the fountain confiner 330 mm, and total height of the reactor 430 mm. The cone base diameter is 20 mm, and the internal diameter of the fountain confiner 54 mm, with its volume being of around 0.8 L. The height from the reactor base to the lower end of the confiner is 105 mm.

The gas inlet diameters (D_0) used are 5.5 and 8 mm for the draft tubes of 8 and 10 mm diameter (D_T), respectively. The base diameter (D_i) was 20 mm independently of the draft tube used. The entrainment zone height (L_H) for the 8 mm draft tube was 15 mm, and two entrainment zone heights have been assayed for the 10 mm draft tube, i.e., 15 and 25 mm. This parameter plays a crucial role on the spouting regime behavior; that is, higher solid circulation rates are attained for longer entrainment zones [40,41]. The total height of all the draft tubes (L_T) is 85 mm. The design and dimensions of the draft tubes are shown in detail in Fig. 2. In order to visually monitor the spouting regime performance throughout the experimental runs, a glass window has been inserted in the reactor lid. The gas cannot leave the reactor through the fountain top, but it has to go down to the lower end of the device in order to attain the desired hydrodynamic regime.

The spouted bed reactor is located inside a two independent section radiant oven, which provides the heat to operate up to 900 °C. The lower section of the oven is used to preheat the gas