Fuel Processing Technology 140 (2015) 245–251

Contents lists available at ScienceDirect

Fuel Processing Technology

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

Influence of bulk solids cross-flow on lateral mixing of fuel in dual fluidized beds

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ARTICLE INFO

Article history:
Received 30 June 2015
Received in revised form 14 August 2015
Accepted 14 September 2015
Available online 20 September 2015

Keywords:
Fluidized bed
Lateral mixing
Cross-flow

ABSTRACT

In typical dual fluidized bed systems — used e.g. in chemical looping combustion or indirect gasification of biomass for production of second-generation biofuels — the bulk solids are continuously circulating between a tall high-velocity riser and a bubbling bed. This circulation results in a solids cross-flow in the bubbling bed, which creates a net convective solids flow. The aims of this paper are to describe this convective flow by means of mathematical modeling and to investigate the effect of the cross-flow of bulk solids on the lateral mixing of fuel particles.

Experiments relevant for industrial conditions are carried out in a fluid dynamically downscaled cold flow model of an existing indirect gasifier. It is found that the velocity field of the bulk solids induced by the solids cross-flow can be described by a potential function obtained from a diffusion equation. As for the fuel particles, their slip respect to the bulk solids cross-flow is quantified using a cross-flow impact factor, θ, which is found to be a linear function of fluidization velocity and in the range 0.18–0.68 for the conditions investigated. Finally, we conclude that the fuel mixing in fluidized beds with a significant cross-flow of bed material can be described by a convection–diffusion equation.

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1. Introduction

This work investigates the influence of solids cross-flow on the lateral mixing of solids in a fluidized bed (bulk and immersed particles in the bed, such as fuel particles). While methodology and results presented in this work are of relevance for other dual fluidized bed (DFB) applications, the authors have chosen indirect gasification as reference application in this paper. The purpose of the gasification process is to convert solid fuels into gaseous ones with the possibility to further upgrade to gaseous or liquid fuels (e.g. through Fischer–Tropsch synthesis). Gasification has been used throughout history by countries with large stocks of coal and with no access to liquid fuels [1], although the price of oil has influenced to what extent coal gasification has played a role. Today, the focus of development work in the areas of gasification has shifted to developing efficient biomass gasification processes for production of high-quality biofuels, possibly in combination with heat and power generation [2]. Compared to the combustion process, gasification involves a more complex set of chemical reactions and has reached a lower level of commercialization. There are few examples of large scale biomass fuelled gasification processes. The indirect gasifiers in Güssing (8 MW) [3] and Göteborg — Chalmers (2–4 MW) and GoBiGas (30 MW) [4–6] — represent projects of industrial scale.

The final products of combustion are water vapor and carbon dioxide and those of gasification are hydrogen and carbon monoxide, a mix referred to as syngas. While combustion is exothermic, gasification is endothermic, i.e. heat is needed to maintain the gasification reactions. The heat required to maintain the endothermic reactions can be supplied in two ways: *directly* or *indirectly* [2] as schematized in Fig. 1. In the *direct* case a small amount of the fuel is combusted to produce heat; thus, steam aimed for gasification is mixed with air required for the partial combustion in the same unit [7]. Having this, while only one reactor is needed for all the chemical reactions, the syngas leaving the gasifier is diluted by combustion products and nitrogen from the air. Therefore expensive gas upgrading is required downstream in order to obtain a high quality product. For direct gasification regular bubbling beds can be used for which solids mixing have been investigated by several authors [8–16].

In the *indirect* case combustion and gasification take place in a DFB system, i.e. in two separate reactors and heat is transferred from the combustor to the gasifier [3,5] maintaining the gasification process. With this configuration, a syngas of much higher rank (theoretically free of nitrogen and combustion products) is produced at the additional cost of having two reactors. The transfer of heat between reactors is provided by means of circulation of bed material. Besides eliminating the need for a significant heat transfer between reactors, the use of fluidized bed reactors offers other advantages such as fuel flexibility and high heat and mass transfer within each reactor. However, the continuous flow of bed material circulating between the two beds induces a

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http://dx.doi.org/10.1016/j.fuproc.2015.09.017
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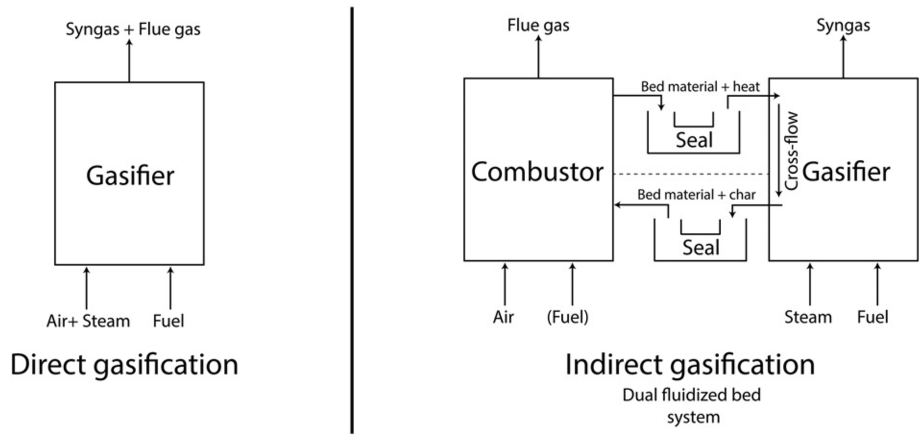

Fig. 1. Direct gasification in a single reactor and indirect gasification using a DFB system.

cross-flow over the gasifier bed which is typically a bubbling bed with fuel entrance at one side and the exit of the bed material to the combustor at the opposite side. Thus, provided a gasifier of industrial scale such bed will have a cross-section of several meters (as opposed to small research reactors which will only have a small cross-section). In dual bed system the influence of the cross-flow have so far only been quantified through residence time distributions of fuel in the gasification reactor [5,17–19] without any deeper investigations on the velocity fields created by solids cross-flow.

Thus, taken together, the lateral mixing of the fuel particles in DFB-systems is a result of convective mixing due to the cross-flow [20,21] and the bubble-induced dispersive mixing [22,23]. The influence of the bulk solids cross-flow on the lateral mixing is fairly unknown and an initial investigation by Sette et al. [21] showed earlier that the velocity field induced by the cross-flow is not homogenously distributed over the bed cross-section. Previous work in the Chalmers 2–4 MW gasifier suggests that the cross-flow makes fuel particles pass through the gasifier bed too fast, resulting in incomplete gasification [20]. Sette et al. [21] showed that using the average cross-flow velocity does not provide a good description of the solids mixing but it is necessary to resolve the velocity field over the cross-section. Thus, in order to understand how these effects can be overcome and to provide knowledge as basis for reliable design and scale up of dual-bed fluidized bed gasification systems, there is a need for further investigations on the fuel mixing including the influence of the cross-flow on the lateral mixing of fuel.

The purpose of this work is to investigate how the convective cross-flow induced by circulating solids in a DFB system can be modeled, to evaluate its influence on the lateral mixing of fuel particles, and to evaluate if a convection–diffusion equation can be used to mathematically describe the fuel mixing in fluidized beds with a significant cross-flow of bed material. This work applies experimental methods previously developed by the authors [24,25] for determining the mixing of the bulk bed-material and the fuel to a system with a significant cross-flow of bulk solids.

2. Theory and experimental methodologies

Despite that mixing in fluidized beds has been investigated for several decades, there is still lack of detailed knowledge on its governing processes, although on a macro level it is obvious that the gas bubbles, rising through the bed, are responsible for mixing of the bed solids [15,26].

2.1. Theoretical background

Three main solids-mixing mechanisms have been identified in previous work [22,23] and these are schematically illustrated in Fig. 2: 1) lifting of solids in the wake of rising bubbles [23], 2) sinking of solids around rising bubbles to fill the gap created by the bubbles [27], and 3) splashing of solids at the surface of the bed, when the bubbles erupt [28,29]. As indicated in Fig. 2 solids is exchanged between mixing cells which enables lateral mixing of solids.

It has been experimentally determined that the gas bubbles rise along preferential paths [30]. The formation of clear bubble paths is enhanced by gas distributors with a relatively low pressure drop typical for fluidized beds of industrial scale where gas-distributor pressure drop has to be kept low to save fan power. Around each of these bubble paths, a flow pattern of solids was found by analyzing the flow of a tracer particle mimicking a fuel particle [17]. The region including the

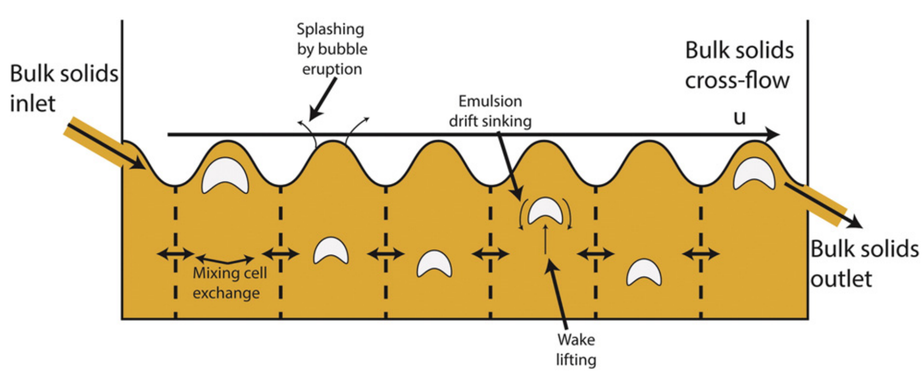

Fig. 2. The three main solids mixing mechanisms induced by gas bubbles and the additional effect of bulk solids cross-flow which induces a net lateral velocity field, *u*.

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