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Measuring fuel mixing under industrial fluidized-bed conditions – A camera-probe based fuel tracking system

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HIGHLIGHTS

- A non-intrusive optical method for industrial fluidized beds is presented.
- Lateral dispersion coefficients for and industrial gasifier are obtained.
- Vertical mixing enhanced by fluidization velocity.
- Vertical mixing is suppressed by cross-flow.

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ABSTRACT

This work presents and applies a camera-based fuel tracking system for quantification of the motion of individual fuel particles at the surface of bubbling fluidized beds operated under hot conditions. In particular a bubbling fluidized bed with a cross section of 1.44 m^2 operated at 800 °C is investigated. Mixing of wood pellets and wood chips is investigated by feeding batches of fuel and applying multi particle tracking to the videos recorded by a specially designed camera probe. The influence of the bulk solids cross-flow and fluidization velocity on the mixing of fuel particles is analyzed.

It is shown that the new fuel tracking method can withstand industrial conditions. Applying the method gives reproducible results and yields lateral dispersion coefficients in the range 10^{-3}–10^{-2} m^2/s for both pellets and wood chips. The lateral mixing of the fuel increases with fluidization velocity and, to a minor extent, with the cross-flow of bulk solids. As observed in previous work, the location of fuel particles on the bed surface confirms the existence of preferred bubble paths, and these are smeared out by the cross-flow of bulk solids. The vertical mixing is hindered by the cross-flow of bulk solids, while it is enhanced by fluidization velocity, which is in agreement with previous research.

1. Introduction

In energy conversion applications bubbling fluidized beds are used for combustion [1] and gasification [2–7]. Fluidized beds are capable of efficiently handling several types of fuels and in recent years efficient use of biomass and waste products has been in the focus of research. Such fuels are characterized by a high content of volatiles, which are released at relatively high rates compared to the rate of char conversion.

Mixing of fuel particles is a key parameter for the overall performance of fluidized bed boilers burning high volatile fuels but also for other fuels when burnt in beds with a large cross-section. Too low lateral mixing rate of the fuel particles results in maldistribution of fast-releasing volatiles, which in turn reduces the boiler performance and increases the risk of emissions. In the vertical direction, sufficient mixing ensures good contact between fuel and combustion air. Thus, sufficiently fast mixing is required in order to ensure complete burn out of fuel [8] and to minimize the number of fuel feeding ports in fluidized bed boilers [9].

In indirect fluidized bed gasifiers, on the other hand, the aim is to control the fuel mixing. These systems (also known as allothermal gasifiers) consist of two interconnected beds coupling a gasifier to a combustor in order to generate the heat needed for the endothermic gasification reactions [10,11]. In the gasifier bed, the lateral mixing of fuel has to be controlled and kept at a moderate level to give the fuel sufficient residence time within the gasifier bed in order to be converted by the gasification reactions (which are slower than the combustion reactions [7]). Thus, too high lateral mixing results in a loss of char from the gasifier to the connected combustor [10]. Furthermore, vertical mixing enables extensive contact between the volatiles released from the fuel

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particles and the bed material, which is particularly relevant when catalytic materials are used as bed material [12].

Olsson et al. [13] conducted experiments in a large scale unit operated under cold conditions, yielding lateral dispersion coefficients two orders of magnitude lower than under hot conditions (for similar operating conditions besides temperature) [13,14], which confirms that experiments at cold conditions fail to capture the behavior of a bed operated under hot conditions even if performed at large scale. Moreover, fuel and bed material are affected to different extent by the action of the rising bubbles owing to their differences in physical properties (i.e. size, shape and density). It was first described by Rowe et al. [15] that lighter particles (flotsam) are preferably dragged upwards by the bubbles while the denser material (jetsam) tends to sink to the bottom of the bed. This vertical segregation may be promoted, in addition to the buoyancy force induced by the density difference, by the lift force induced by the release of volatiles in high volatile fuels (e.g. biomass, low rank coals) [16,17], which is also difficult to reproduce at cold conditions. Yet, visual observation of the fuel behavior at the bed surface of a hot large scale bed [18] indicates that such effect mostly appears at very low velocities, much lower than typically applied in combustors of industrial size.

In addition to the bubble-induced mixing found in fluidized beds there is an additional contribution to the fuel mixing in systems of interconnected fluidized beds such as indirect gasifiers and chemical looping combustion units, i.e. in systems which have a significant circulation of bulk solids between the reactors [5,6,19–22]. The cross-flow induced mixing mechanism is convective in type, as opposed to the bubble-induced mixing, which has a dispersive nature on a macroscopic scale (although also governed by convective movements from a mesoscopic point of view due to the bubble flow). The cross-flow induced mixing mechanism has so far only been experimentally quantified in fluid-dynamically downscaled fluidized beds and focusing only on the lateral mixing [19,20] and neither in large scale equipment nor in beds operating under hot conditions. Thus, there is a need for a fuel tracking measurement procedure for quantification of the lateral fuel mixing under industrial conditions.

The aim of this work is to develop an experimental method for direct fuel tracking under industrial conditions (a large scale unit at a temperature around 800 °C) by means of a new video recording procedure. The effect of fuel density, solids cross-flow and fluidization velocity on mixing of fuel is investigated in the bubbling regime. Previous works (both experimental and numerical) on dual fluidized bed systems have not considered the effect of cross-flow, thus this work provides new insight into systems of interconnected fluidized beds.

2. Theory

Even though solids mixing in fluidized beds has been investigated for several decades, there is still lack of detailed knowledge on its governing processes. However, researchers agree that gas bubbles, rising through the bed, inducing mixing of the bed solids [23,24]. Three mixing mechanisms have been identified in previous work [25,26] (1) lifting of solids in the wake of rising bubbles [25], (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].

At a macroscopic scale, given the solids flow arranged in a repetition of isotropic flow structures, the lateral mixing of solids can be described in analogy with a Markov chain, which is mathematically described by the diffusion equation:

$$\frac{\partial C}{\partial t} = D\nabla^2 C \tag{1}$$

where D is generally referred to as a dispersion coefficient and is assumed to be equal for the two lateral directions and can be evaluated using Einstein's [30] equation for Brownian motion:

$$D = \frac{(\Delta x)^2}{2\Delta t} \tag{2}$$

where Δx is the fuel-particle displacement between the fuel feeding location and subsequently observed locations and Δt is the elapsed time. By providing a characteristic length Eq. (2) can be rewritten as:

$$D = \frac{u_{avg}\cdot L}{2} \tag{3}$$

The average fuel velocity (u_{avg}) can be decomposed into the fuel velocity on the bed surface and inside the bed, weighted by the respective fractions of fuel according to:

$$u_{avg} = u_{surf}X_{surf} + u_{bed}(1 - X_{surf}) \tag{4}$$

In the case of dual fluidized bed systems there is a continuous circulation of bulk solids which creates a solids cross-flow in the bubbling bed. This cross-flow yields a convective flow field which is superimposed on the dispersive mixing originated by the bubble flow. For fuel particles, the transport equation describing fuel concentration can be written as:

$$\frac{\partial C}{\partial t} + \nabla\cdot(Cu) = \nabla\cdot(D\nabla C) \tag{5}$$

Eq. (5) expresses both bubble-induced (dispersion) and cross-flow induced mixing of fuel where u is the velocity field of the fuel particles, more information on the importance of cross-flow is given by Sette et al. [31].

If no explicit information on the velocity field of fuel particles is available a modified lateral fuel dispersion coefficient can be defined to lump the effect of regular bubble-induced mixing and the cross-flow induced mixing, i.e.:

$$\frac{\partial C}{\partial t} = \frac{\partial}{\partial x}\left(\left(D_x^{bubble} + D_x^{cross}\right)\frac{\partial C}{\partial x}\right) + \frac{\partial}{\partial x}\left(\left(D_y^{bubble} + D_y^{cross}\right)\frac{\partial C}{\partial x}\right) \tag{6}$$

Note that if the velocity field is different in the two lateral directions the apparent dispersion will appear as non-isotropic, i.e. the lumped dispersion coefficients in the two lateral directions are not equal anymore, as concluded from Eq. (6).

3. Experimental setup

The fuel tracking method developed in this work is based on video filming the bed from above together with post processing of the video frames. In this work, the camera (Unibrain 630b) was mounted in the Chalmers indirect gasifier (shown in Fig. 1), which is operated at 800 °C. Fig. 1 provides a view of the front side where the camera probe is mounted (more details about the gasifier system which is in meters scale are provided elsewhere [10,32]). The probe is mounted at an angle of 45° toward the bed surface and the tip of the probe is located approximately 1.0 m above the bed surface. Fig. 2 shows a schematic drawing of the probe indicating the measures taken to allow a camera to be mounted into a bubbling fluidized bed. Given the size of the equipment and the frame rate used it is possible to resolve velocities up to 30 m/s. The camera record videos in the visible light spectrum and Table 1 summarizes the camera specifications.

The probe needs to be cooled in order to ensure functionality of the camera and avoid cracking of the front glass due to thermal stresses. Therefore, the probe is equipped with a water cooling jacket with adjustable water flow to maintain a temperature at the camera location below 25 °C. The front glass needs also to be cooled to avoid cracking (occurring at roughly 800 °C) while a high