Chemical Engineering Journal 313 (2017) 144–156

Contents lists available at ScienceDirect

Chemical Engineering Journal

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

A simple and robust approach for early detection of defluidization

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HIGHLIGHTS

- A simple approach is presented for the early detection of defluidization in a bubbling gas-solid fluidized bed.
- The new approach relies on the simultaneous monitoring of temperature and pressure signals.
- It effectively predicted the onset of agglomeration minutes to hours before complete defluidization.
- It was robust with respect to the changes in gas velocity, operating temperature, and bed inventory.

ARTICLE INFO

Article history:
Received 20 July 2016
Received in revised form 15 October 2016
Accepted 1 December 2016
Available online 2 December 2016

Keywords:
Defluidization detection
Gas-solid fluidized bed
Bubbling regime
Temperature measurements
Pressure measurements

ABSTRACT

This study presents a simple approach for the early detection of agglomeration in a bubbling gas-solid fluidized bed. This monitoring approach is based on the simultaneous measurements of local temperatures and the in-bed differential pressure drop from the well-stabilized section of the bed. Defluidization experiments (800–1000 °C) showed that when a bubbling gas-solid fluidized bed approaches complete defluidization the average in-bed differential pressure drop progressively decreases from a reference value obtained under normal conditions while the temperature difference along the axis, particularly between a temperature reading right above the distributor plate and others at higher levels within the dense bed, simultaneously increases. This novel approach was thus proposed for the concurrent occurrence of these drifts to provide an opportune recognition of the onset of agglomeration in a bubbling gas-solid fluidized bed. The results demonstrated that it could effectively detect the defluidization condition minutes to hours before the complete defluidization state depending on the growth rate of agglomeration within the bed. Two pairs of detection thresholds for the timely recognition of agglomeration in bubbling fluidized beds of coarse silica sand particles were introduced according to the observations made in this study. The approach exhibited minimal sensitivity to variations in the superficial gas velocity (±10%), operating temperature (±100 °C), and bed inventory (±20%) while both legs of the in-bed differential pressure transducer were well below the splash zone and above the jetting zone formed in the vicinity of the distributor plate.

1. Introduction

Despite their widespread industrial application at elevated temperatures, gas-solid fluidized beds are prone to agglomeration potentially leading to defluidization problems. Processes in the area of polyolefin production and energy conversion (combustion and gasification of a wide variety of solid fuels, including biomass, waste, and coal or their blends) are relevant processes that regularly experience these problems [1]. An increased level of cohesive interparticle forces (IPFs), which can result from different mechanisms, principally governs these unwanted phenomena. Sintering the bed materials at high temperature is the major reason for agglomeration in the case of the fluidized bed production of polyethylene and polypropylene [2]. Alternatively, capillary IPFs due to the formation of low-melting eutectics are the main cause of agglomeration in fluidized bed energy conversion processes [3–7]. The ongoing agglomeration can ultimately lead to a complete blockage of the distributor plate or defluidized state and, hence, a forced plant shutdown [8,9], which is followed by a cumbersome cleaning step and restarting of the plant. Therefore, it is of great importance to identify the onset of the agglomeration phenomenon at an early stage leaving enough time to implement counteractive measures. This reduces downtime and production loss and avoids the cleaning and start-up efforts resulting from a full plant shutdown.

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http://dx.doi.org/10.1016/j.cej.2016.12.002
1385-8947/

Nomenclature

Acronyms
CSB40 coated sugar beads at 40 °C
HDFs hydrodynamic forces
IPFs interparticle forces
RPT radioactive particle tracking
SB20 sugar beads at 20 °C

Symbols
d_p average particle size (μm)
$\bar{t}_{idle}$ average idle time (sec)
$T4$ temperature reading of thermocouple No. 4 (°C)
$T6$ temperature reading of thermocouple No. 6 (°C)
$T11$ temperature reading of thermocouple No. 11 (°C)
U_{mf} minimum fluidization velocity (m/s)
U_g superficial gas velocity (m/s)

Greek letters
$\overline{\Delta P}_{in\text{-}bed}$ average in-bed differential pressure drop (Pa)
$(\overline{\Delta P}_{in\text{-}bed})_{eval}$ evaluation average in-bed differential pressure drop (Pa)
$(\overline{\Delta P}_{in\text{-}bed})_{ref}$ reference average in-bed differential pressure drop (Pa)
ΔT_{sel} selected temperature difference along the axis (°C)
$(\Delta T_{sel})_{eval}$ evaluation selected temperature difference along the axis (°C)
$(\Delta T_{sel})_{ref}$ reference selected temperature difference along the axis (°C)
ρ_p particle density (kg/m^3)

Various approaches differing either in the type of measurement technique employed or the signal analysis have been proposed for the early detection of defluidization conditions [1,8,10–24]. The goal of these approaches is to trigger an alarm to apply an operational/counteractive measure. The effectiveness, ease of implementation and operation, and robustness are regarded as the most important features to be readily adopted in industry. Pressure and temperature measurements are the only routine measurements in industry to provide hydrodynamic insight about the fluidized state of the particles [25].

The measurement of pressure signals from a gas-solid fluidized bed offers several advantages over other techniques, such as: (i) large measurement volume (in the order of some tens of centimeters [26]), (ii) moderate cost, (iii) non-intrusiveness, and (iv) ease of implementation [27,28]. Furthermore, when sampled at a high enough frequency the signal contains a lot of information about the flow dynamics of the fluidized bed (i.e., bubble formation, coalescence, eruption, and passage) [29,30]. The variation in the particle size distribution resulting from the agglomeration process can effectively alter these hydrodynamic parameters [8]. Compared to pressure probes, thermocouples provide more localized measurements of the bed hydrodynamics. The temperature measurements attained by these probes contain information on the degree of solids mixing within the bed [6], i.e., the presence of a more uniform temperature profile throughout the bed indicates a better quality of solids mixing. These measurements, however, need considerable insight into the corresponding process to yield a correct interpretation [25]. A review of earlier studies [1,8,10–24] reveals that the sole reliance on either temperature or pressure signals was not sufficient to result in a simple, robust, and reliable approach for detecting bed agglomeration. Nevertheless, preliminary results of the simultaneous applications of temperature and in-bed differential pressure signals, reported by our group [31], showed a promising performance.

Since there was not a thorough understanding about the detailed influence of IPFs on the fluidization characteristics of a bubbling gas-solid fluidized bed, the general impression was that analyzing the pressure fluctuations recorded from a fluidized bed could provide more useful information for the establishment of a monitoring approach than the averaged pressure values. However, through the application of a polymer coating approach [32,33] at near-ambient conditions [31] to increase the level of IPFs in the bed, it was observed that the average in-bed differential pressure drop decreased by enhancing the degree of IPFs at identical fluidizing gas throughputs in the bubbling regime. An increased capacity of the emulsion phase to hold the fluidizing gas inside its structure at higher levels of IPFs [31,34] is principally responsible for this evolution [31]. The presence of considerably large/oblong bubbles at high levels of IPFs can additionally reduce the average in-bed differential pressure drop [31]. Also, when the level of IPFs increases in a bubbling gas-solid fluidized bed, even in the absence of permanent agglomerates, it can be expected that the bed will present a less uniform temperature distribution especially in the axial direction when comparing it against normal conditions (i.e., in the virtual absence of IPFs). It is due to a decrease in the quality of solids mixing when cohesive IPFs are present in the bed [35]. It should be borne in mind that due to the inherent axial movement of bubbles in the bed, which is responsible for the solids circulation within the bed, temperature differences in the axial direction may be considerably less than in the radial direction. In large industrial scale fluidized beds this can be the result of solid inlet and waterwalls, while in smaller scale reactors it can be the result of heat transfer with the walls (cooling or heating). It implies that the application of an axial temperature difference generally located away from walls and solid inlets should be preferred for an agglomeration detection approach. In general, the axial temperature profile, as long as it is located away from the effects of the wall and inlet, should provide a better indication of the bed tendency to agglomeration/defluidization resulting from the presence of a high level of IPFs in the bed. Thus, the new detection approach was established based on the fact that since the level of IPFs progressively increases in a fluidized bed approaching complete defluidization, both observations should co-exist. The simultaneity of these two evolutions combined with the complete independence of pressure and temperature measurements lends credence to the newly proposed approach to result in a reliable early recognition criterion.

This investigation is a continuation of the previous study of our group [31] proposing a simple, efficient, and robust approach for the opportune detection of defluidization conditions by simultaneous applications of pressure and temperature signals. At first, the most sensitive location for the measurement of temperature within the dense bed, with respect to the variation of IPFs, was identified with the help of the radioactive particle tracking (RPT) technique. The validity of the novel recognition approach for the early warning of defluidization incidents occurring during the propane and solid fuel combustion was subsequently verified through very difficult defluidization tests in a pilot scale bubbling bed of coarse silica sand particles at high temperature (800–1000 °C). Two pairs of detection thresholds relevant to industrial fluidized bed combustion and gasification of different solid fuels employing coarse silica sand as the bed materials were introduced according to the experimental