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# Performance evaluation of different approaches for early detection of defluidization

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ABSTRACT

Identifying the onset of an agglomeration phenomenon at an early stage in processes utilizing gas-solid fluidized beds that operate under the influence of cohesive interparticle forces affords enough time to apply counteractive strategies and avoid a disastrous agglomeration of particles potentially leading to complete bed defluidization. In this paper, we compare the performance of different leading approaches proposed in the open literature for the advanced detection of defluidization. The approaches include the single-signal-monitoring of evolutions of total bed pressure drop, standard deviation of pressure signals, or *S*-value from the attractor comparison analysis as well as the simultaneous-monitoring of temperature and in-bed differential pressure signals during the process. The results show that the simultaneous-monitoring of temperature and in-bed differential pressure signals provided the best prediction of the onset of agglomeration while it demonstrated the least sensitivity to the changes in gas velocity, operating temperature, and bed inventory.

## 1. Introduction

Different approaches have been proposed in the open literature for the early detection of defluidization conditions resulting from the presence of cohesive interparticle forces (IPFs) in a bubbling gas-solid fluidized bed. They differ either in the type of measurement technique adopted or in the signal analysis. The ultimate goal of these approaches is to trigger an alarm at an early stage of the agglomeration phenomenon to apply an operational/counteractive measure preventing a forced plant shutdown.

Siegell [1] and Tardos et al. [2,3] were among the first to report that a sudden decrease in the total bed pressure drop takes place upon defluidization as most of the fluidizing gas passes through the bed in large channels. With this approach, detection is often too late [4,5] and the situation is irreversible without a shutdown. The application of local measurement techniques with small detection volume, such as capacitance, optical fiber, heat transfer, and triboelectric probes, does not bear high industrial interest because a recognition approach based on these instruments requires many measurement points for an industrial gas-solid fluidized bed [6]. In addition, pressure and temperature measurements are only common in industrial fluidized bed applications to provide hydrodynamic insight about the fluidized state of the particles [7].

Since pressure signals, when sampled at a high enough frequency, contain a lot of information about the fluidization behavior of a gas-solid fluidized bed (i.e., bubble formation, coalescence, eruption, and passage) [8,9] and since there was a lack of understanding about the detailed impact of interparticle forces on the flow dynamics of a bubbling gas-solid fluidized bed, different detection approaches have been proposed based on analyzing the pressure fluctuations recorded from a fluidized bed rather than monitoring the averaged pressure values. The simplest property of the pressure fluctuations, i.e., variance of pressure signals, was exploited by Chirone et al. [10] and Scala and Chirone [11] for the timely recognition of defluidization conditions. Nevertheless, the standard deviation (or variance) of pressure fluctuations is highly sensitive to the variations of superficial gas velocity $U_g$. Moreover, increasing the level of IPFs in a bubbling gas-solid fluidized bed can result in a multiplicity of behaviors affecting the magnitude of the standard deviation of pressure signals in different ways [12]. Therefore, this approach cannot be qualified as a reliable approach for the early recognition of agglomeration in industrial installations, where significant fluctuations in the gas supply are normally encountered [13,14]. Furthermore, van Ommen et al. [15] demonstrated that the spectral analysis of pressure signals is relatively insensitive to small changes in the particle size distribution, and thus cannot be adopted as a suitable detection approach, either.

Among approaches employing non-linear time series analysis, the S-statistic test has shown the best performance for the early detection of defluidization in both laboratory and pilot scale fluidized beds [14,16]. With this monitoring approach, consecutive pressure (evaluation)

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time series, which are recorded at a high frequency during the operation, are compared with a reference time series that reflects normal operation [17]. The comparison is made with the help of the S-statistical test introduced by Diks et al. [18] on the reconstructed attractors from the reference and evaluation time series. An attractor is a collection of points that results from the projection of successive pressure values from the corresponding time series into an *n*-dimensional state space [14]. It represents the dynamics of the system in the state space [19]. With the attractor reconstruction, all properties of the original signal in the time domain are preserved with the exception of the standard deviation, thus decreasing the sensitivity of the approach to changes in the superficial gas velocity [13,14,16,17]. The *S*-value indicates the dimensionless distance between the two attractors [13,14,16]. When the reference and evaluation pressure signals exhibit identical dynamics, the *S*-value has an expectation of zero and a standard deviation of unity. If the *S*-value is greater than 3, the dynamics of two time series significantly differ from each other with more than 95% confidence according to the null hypothesis [17]. Therefore, in the case of early detection of agglomeration, the *S*-values greater than 3 are sought. More details about this approach can be obtained elsewhere [17].

Despite its success in the timely recognition of defluidization conditions based on earlier reports, the S-statistics has its own limitations. They can be listed as follows: (i) it is necessary to register the pressure signals either at a high frequency (>100 Hz) or for a long time; (ii) the performance of the test is highly sensitive to the careful selection of its critical parameters, including the embedding dimension $m$, time delay $\tau$ (normally equal to 1), band width $d$, and segment length $L$. An inappropriate selection of these parameters would either result in the reconstructed attractors becoming too smooth, i.e., not showing any difference when there is a significant difference in the bed behavior, or making the test very sensitive resulting in *S*-values greater than 3 for cases with similar dynamics; (iii) it requires conducting many complex mathematical computations; (iv) as the approach solely compares the similarity of the reference and evaluation signals to mark the point where a significant change is realized, a fundamental understanding about how the bed behavior has evolved over the course of the agglomeration process can hardly be achieved; (v) if care is not taken, it might generate occasional false alarms, particularly when a corrective measure, e.g., reduction in the operating temperature, is applied to a cohesive agglomerating fluidized bed [14]. The sole dependence of the recognition approach on the pressure measurement reduces its applicability under different operating conditions as stressed here for the last drawback.

The temperature measurements achieved by thermocouples provide a local measure of the bed behavior. Although these measurements can provide indirect information about the degree of solids mixing within the bed [20], they need deep insight into the corresponding process to yield a correct interpretation [7]. Therefore, the sole application of either pressure or temperature signals cannot lead to an efficient and robust approach for the timely detection of defluidization.

Shabanian et al. [5] have recently proposed a novel approach for the early detection of agglomeration based on the simultaneous applications of temperature and in-bed differential pressure signals. The detection approach was established based on the observations made on the influence of IPFs on the hydrodynamics of a gas-solid fluidized bed. Upon increasing the level of IPFs, the average in-bed differential pressure drop measured from the well-stabilized section of a dense bed, i.e., well below the splash zone and above the jetting region close to the distributor, and the quality of solids mixing decrease for a given superficial gas velocity in the bubbling fluidization regime [5]. The latter drift results in a less uniform temperature profile along the axis of a high temperature fluidized bed [5,21]. Therefore, since the level of IPFs progressively increases in a cohesive bubbling bed approaching the complete defluidization state, this detection approach was based on the fact that the average in-bed differential pressure drop and the temperature difference along the axis simultaneously decreases and increases, respectively, during this evolution. This approach demonstrated great performance in predicting the onset of agglomeration minutes to hours before complete defluidization. Despite its promising performance, it may lose its ability if the development of the agglomeration process concurrently impacts the whole bed during which the relative temperature difference along the bed height remains unchanged. Two sets of detection thresholds were introduced by Shabanian et al. [22] to trigger the high and high-high alarms of the onset of agglomeration in the case of industrial fluidized bed combustors and gasifiers of low grade solid fuels, where coarse silica sand is adopted as the bed material. According to the proposed criteria, the high alarm is issued when the evaluation average in-bed differential pressure drop $(\overline{\Delta P}_{in-bed})_{eval}$ decreases more than 6% relative to its reference value $(\overline{\Delta P}_{in-bed})_{ref}$ while the evaluation selected temperature difference along the axis $(\Delta T_{sel})_{eval}$ increases by more than 100% from the corresponding reference value $(\Delta T_{sel})_{ref}$. The high-high alarm is issued when $(\overline{\Delta P}_{in-bed})_{eval}/(\overline{\Delta P}_{in-bed})_{ref} \leq 0.90$ and $|(\Delta T_{sel})_{eval}/(\Delta T_{sel})_{ref}| \geq 3$.

In this work, we compare the performance of four different approaches for the early detection of defluidization. They are as follows: (1) monitoring the average total bed pressure drop, (2) monitoring the standard deviation of in-bed gauge pressure signals, (3) monitoring the *S*-value from the attractor comparison analysis, and (4) simultaneously monitoring the temperature and in-bed differential pressure signals. Also, the robustness of the above approaches with respect to the changes in $U_g$ (±10%), operating temperature (±100 °C), and bed inventory (±20%) will be examined. The evaluations are made under identical high temperature conditions.

## 2. Experimental

The experiments were carried out in the same experimental rig that was employed in the studies by Shabanian et al. [5,22], Sauriol et al. [23], and Shabanian and Chaouki [12], and only a brief description of the unit will be given here. The pilot scale rig was a near-atmospheric refractory-lined fluidized bed reactor with a fluidizing section of 20 cm I.D. by 97 cm tall, which was capable of withstanding high temperatures up to 1050 °C. The bed was equipped with a bubble cap distributor plate containing 9 caps each having 4 holes 6.35 mm in size on its perimeter. Dried and filtered air was adopted as the fluidizing gas.

The temperature profile within the bed were monitored with the help of 14 OMEGA type K thermocouples. They were positioned along the axis of the fluidized bed with the bottommost one located at the bed center and 5 cm above the distributor plate. These temperature measurements allowed for the verification of the expanded bed height and provided a local measure of the bed behavior. Pressure measurements were attempted with the help of two differential and a gauge pressure transducers. One differential pressure transducer (JUMO, 404304/000-415-415-28-298, 0–160 mbar) approximately measured the total bed pressure drop (5–130 cm in height). The second differential pressure transducer (JUMO, 404304/000-414-415-28-298, 0–100 mbar) recorded the differential pressure drop from the well-stabilized section of the dense bed (15–45 cm above the distributor plate). A gauge pressure transducer (OMEGA, PX309-002G5V, 0–2 Psig) was located at an axial position of 30 cm above the distributor plate within the dense bed to provide a global picture from the bed. The experimental rig and spatial placements of pressure transducers are schematically shown in Fig. 1.

Coarse silica sand ($d_p = 820$ μm, $\rho_p = 2650$ kg/m$^3$; $d_p$ is the mean particle size and $\rho_p$ is the particle density) was selected as the bed material for the high temperature runs. This is close to the group B/group D boundary based on Geldart's classification [24], which is, however, only applicable at ambient conditions. For most runs a bed inventory of 26 kg was fed into the reactor. It gave an effective bed inventory of approximately 23 kg after accounting for the dead zones, i.e., side ports of the reactor. This corresponds to a static bed height of about 55 cm. The