EARLY AGGLOMERATION RECOGNITION SYSTEM (EARS)

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ABSTRACT: In fluidised-bed combustion and gasification of biomass and waste, agglomeration of bed/ash particles is a major problem area. This paper deals with a new method for monitoring and controlling fluidised-bed hydrodynamics, which enables the recognition of agglomeration in an early stage and provides control measures to prevent further agglomeration and defluidisation. The method, named Early Agglomeration Recognition System (EARS), is based on recognising significant differences between reference time-series of pressure fluctuations and successive time-series measured during prolonged plant operation. The early recognition provides a time interval for taking dedicated actions to counteract the agglomeration. EARS thus can be a tool helping plant operators in preventing agglomeration induced plant shutdowns and minimising bed material make-up and residue production. Results are presented of small-scale experiments showing the effectiveness and selectivity of the early agglomeration recognition. Subsequently, the development of control strategies is discussed.

Keywords: agglomeration, fluidised bed, control systems

1 INTRODUCTION

In fluidised-bed combustion and gasification of biomass and waste, agglomeration of bed/ash particles is a major problem area. With continuous fuel feeding, this bed/ash agglomeration is a self-promoting process. At the onset of agglomeration, the fluidisation behaviour gets disturbed due to the formation of particle clusters and, as a result, a uniform heat distribution is no longer possible. Local peak temperatures promote further agglomeration, which may ultimately lead to complete defluidisation and consequently a forced plant shutdown. With existing on-line monitoring techniques, based on measuring pressure drop or temperature differences, detection is often too late and an irreversible situation has already been created. Therefore, it is common practice to maintain a relatively large make-up rate for the bed material in order to minimise the risk of severe agglomeration. However, this not only leads to a relatively large and costly bed material make-up and residue production, but still forced plant outages cannot be prevented completely.

At ECN, considerable R&D work is dedicated to obtaining a better understanding of agglomeration mechanisms [1,2] as well as the development of more adequate monitoring and control methods. At Delft University of Technology (DUT), substantial research effort is aimed at analysing and controlling fluidised-bed hydrodynamics, which recently resulted in a novel monitoring method for fluidised beds [3]. DUT and ECN have now joined forces to combine this monitoring method with effective control strategies. This paper describes the resulting method for *monitoring and controlling* fluidised-bed hydrodynamics, named Early Agglomeration Recognition System (EARS). The method is aimed at recognising the onset of agglomeration in an early stage and providing control measures to prevent further agglomeration and defluidisation.

In this paper, the principles of EARS are explained. Then, results of small-scale experiments are presented showing the effectiveness and selectivity of the monitoring method. Finally, the development of effective control strategies making use of the early recognition is discussed.

2 METHODOLOGY

2.1 Earlier monitoring methods

In literature, several methods have been proposed to monitor fluidised-bed hydrodynamics. Most of the methods are based on pressure drop or temperature difference measurements in the bed. However, earlier work [4,5] showed that pressure drop and temperature differences are not sufficiently accurate '*early* warning indicators' for changes in the hydrodynamics. In general, agglomeration could not be detected until defluidisation had occurred. In that case it is often too late: a suitable monitoring method should give an *early* warning to *prevent* defluidisation.

Since pressure *fluctuations* contain a lot of information about the fluidised-bed dynamics, it seems more attractive to base a monitoring method on these fluctuations instead of on averaged pressure values. The simplest property of pressure fluctuations to consider is the pressure intensity. However, the pressure intensity strongly depends on the superficial gas velocity. Therefore, it is not suitable for detecting changes in the hydrodynamics in industrial installations, in which the gas supply normally shows significant variations.

Spectral analysis is often used to characterise different fluidisation regimes, but is rarely reported as being used for (on-line) monitoring of the state of fluidisation, since it is rather insensitive to changes in particle size (distribution).

Another way of detecting changes in pressure fluctuations is by using techniques from non-linear time-series analysis, often referred to as chaos analysis. In the past decade, a number of monitoring methods based on these techniques have been proposed. However, these methods often lacked proper statistics to decide whether an indicated change in the fluidised state of the bed is significant and their selectivity for detecting agglomeration (*i.e.*, a change in particle size) was not determined. Although EARS is also based on non-linear time-series analysis, the effectiveness for early agglomeration recognition and the selectivity have now been given much emphasis, as is described in the next sections.

2.2 EARS

The monitoring method of EARS compares pressure time-series (high-frequency pressure measurements from the fluidised bed) in a statistical way using non-linear analysis techniques [3]. First, a reference time-series, reflecting the optimum or required fluidisation state of the bed, should be obtained. During operation of the fluidised bed, consecutive pressure time-series (evaluation time-series) are measured. The time-series are compared as a whole using a mathematical technique called ‘attractor reconstruction’. The only property excluded from comparison is the standard deviation to reduce the sensitivity to the superficial gas velocity.

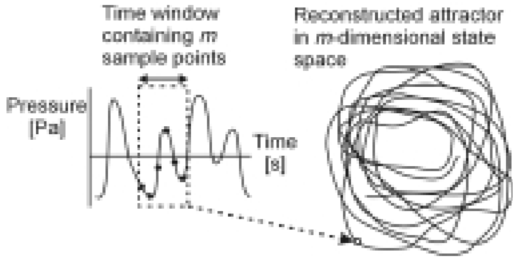

Figure 1: The reconstruction of an attractor in the m-dimensional state space from a pressure time series.

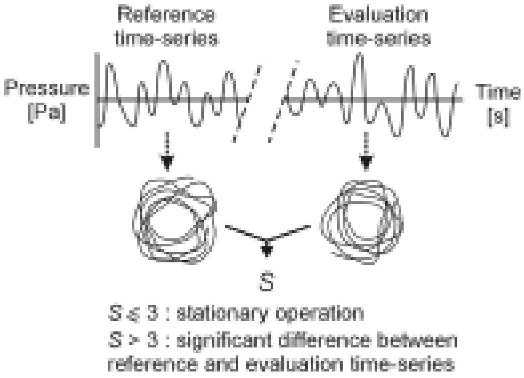

Figure 2: Schematic representation of the EARS monitoring method.

Both reference and evaluation time-series are transformed into an attractor, *i.e.*, a multi-dimensional distribution of delay vectors containing successive pressure values (see Figure 1). The attractor represents consecutive states of the dynamic system; it can be seen as a ‘fingerprint’ of the fluidised-bed hydrodynamics. The reference attractor and the evaluation attractor are compared by calculating a statistic *S* [3] (see Figure 2). *S* represents the dimensionless distance between the two attractors. In this way all attractor properties are taken into account. For attractors generated by the same dynamics or mechanism, *S* has an expectation value of zero and a standard deviation of unity. When *S* is larger than three, we know with more than 95% confidence that the two attractors differ significantly, which means that the hydrodynamic behaviour of the fluidised bed has changed. This is an indication of the onset of agglomeration, as has been shown earlier [6].

3 EXPERIMENTAL

To determine the effectiveness and selectivity of the early recognition of agglomeration, bench-scale gasification tests and cold-flow experiments were conducted. The bench-scale gasification tests were carried out in a 7.4 cm i.d. bubbling-fluidised-bed gasifier/combustor shown schematically in Figure 3. In the tests, miscanthus was gasified with air at a constant temperature of 760 °C. The fuel was fed into a quartz sand bed (median particle diameter 340 µm) by means of a screw feeder at a rate of approx. 1 kg/h and gasified at an equivalence ratio of approx. 0.2. At these settings, the sand bed was fluidised at 5 times the minimum fluidisation velocity (excluding the large contribution from pyrolysis products).

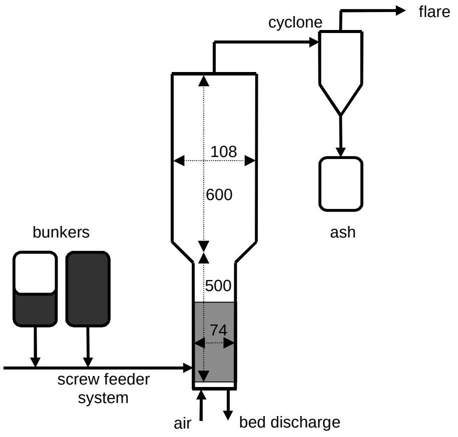

Figure 3: Schematic representation of the 1 kg/h bubbling-fluidised-bed gasifier/combustor; sizes in mm.

Cold-flow experiments with changes in gas velocity and bed mass were carried out in an 80 cm i.d. column, containing sand with a median particle diameter of 530 µm; the minimum fluidisation velocity of this sand is 0.14 m/s. In a second set of cold-flow experiments, agglomeration was induced by adding water to a bed of coke particles. These experiments were carried out in a 15 cm i.d. column. The coke particles had a median particle diameter of about 100 µm and a minimum fluidisation velocity of 1.15 cm/s. The experiments were conducted with a bed mass of 2.4 kg and a fluidisation velocity of 5 cm/s. Water was dropped onto the bed surface with a flow rate of 3 ml/min.

In all the experiments, the local pressure in the bed was measured using probes with a length of 10-60 cm and an internal diameter of 4 mm. These dimensions guarantee an undisturbed transfer of the signal in the frequency range of interest [7]. In the gasification tests, a purge flow was used, while in the cold-flow experiments, the end of the probes was covered by wire gauze to prevent particles from blocking the probe. Piezoelectric pressure sensors of Kistler type 7261 connected to the probes were used to measure the pressure fluctuations. The signals were low-pass filtered with a cut-off frequency of one half or one third of the sample frequency, satisfying the Nyquist criterion. Subsequently, 16 bits analogue-to-digital conversion was applied at a sample frequency of 200 or 400 Hz.

4 RESULTS AND DISCUSSION

4.1 Effectiveness and selectivity

In the gasification tests, agglomeration led to defluidisation of the bed in approx. 3-4 hours. SEM analysis showed that the agglomeration appeared to be of the “coating-induced” type [1,2]. A (uniform) coating layer was formed on the surface of the quartz sand grains, consisting of an amorphous silicate with alkali and calcium as the main other components. In this type of agglomeration, neck formation occurs between coatings of individual grains at certain critical conditions (*e.g.*, coating thickness and viscosity [2]), which initiates agglomeration. For one of the tests, values for two conventional agglomeration indicators (pressure drop (ΔP) and temperature difference (ΔT) over the bed) as well as *S*-values calculated according to EARS are presented in Figure 4. From this figure it can be concluded that *S* increases to values above the critical value *S*=3 significantly before any deviations can be observed for the conventional indicators. In this particular test, the gain in time ranges from 20 to 35 minutes and depends amongst others on the choice of the size of the reference and evaluation time windows.

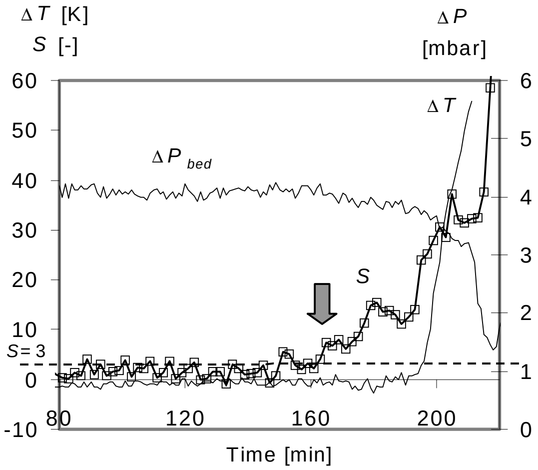

Figure 4: The effectiveness of EARS for bench-scale gasification of miscanthus.

It appears that EARS enables detection of the *onset* of agglomeration, while the pressure drop and temperature difference over the bed only change significantly upon severe agglomeration and defluidisation.

Since EARS is used to detect the sporadic event of agglomeration, it should not indicate changes in hydrodynamics due to much more frequent events, *e.g.*, small variations in superficial gas velocity or bed mass. To decrease the sensitivity to fluctuations in gas velocity and bed mass, the pressure signal is normalised and the probes are positioned approx. halfway the gas distributor plate and the bed surface. The insensitivity to changes in gas velocity is illustrated by cold-flow experiments in the 80 cm i.d. column. In these experiments, the bed mass was 600 kg sand and the settled bed height was 80 cm. The pressure probe was located at 44 cm above the distributor plate. At every gas velocity, four time-series of 5 minutes were evaluated by the monitoring method; a gas velocity of 0.35 m/s was used in the reference situation. Figure 5 shows that for variations of the gas velocity smaller than 10% the *S*-statistic stays below 3: the method does not indicate a significant change.

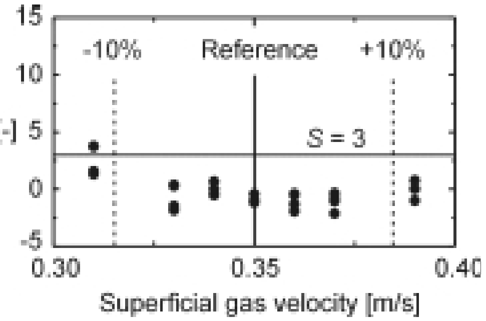

Figure 5: Influence of the superficial gas velocity on the *S*-value.

To illustrate the insensitivity to changes in bed mass, the mass of sand in the 80 cm i.d. column was increased from 550 kg (settled bed height 73 cm) to 700 kg (settled bed height 93 cm) in six steps. The superficial gas velocity was 0.40 m/s. The pressure probe was again located at 44 cm above the distributor plate. At every bed mass, six time-series of 5 minutes were evaluated by the monitoring method; a bed mass of 625 kg was used in the reference situation. Figure 6 shows that the *S*-value stays below 3 for all bed mass changes smaller than 10%.

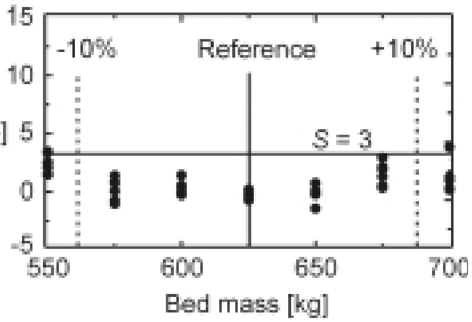

Figure 6: Influence of the bed mass on the *S*-value.

When larger variations in operating conditions are encountered, a reference time-series should be used for *every* typical set of operating conditions. In this way, agglomeration can still be detected.

4.2 Development of control strategies

Having established the effectiveness of EARS as an early agglomeration indicator in relatively small-scale installations, ECN and DUT then focused their activities on the development of control strategies and on scale-up and full-scale validation of the combined monitoring and control method.

Although many control strategies are possible in principle, such as changing the bed temperature, increasing the superficial gas velocity and local gas injection, particular attention is paid to adjustment of the bed material make-up rate. In biomass gasification and combustion, this is the common control parameter. A reliable early recognition of the onset of agglomeration should enable the prevention of agglomeration induced plant shutdowns at a minimal bed material make-up and residue production.

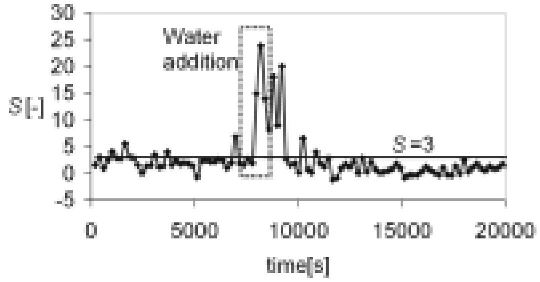

Figure 7: The *S*-value before, during, and after the addition of water to a bed of coke particles. The dashed rectangle indicates the period of water addition.

As a first step in extending the method into a *monitoring and control* method, tests were conducted in the 1 kg/h gasifier/combustor with a periodic discharge and make-up of bed material. It appeared that the *S*-value could be kept stable below *S*=3. Furthermore, it was investigated if EARS can rightly indicate the return to the original state after giving an alarm. To this purpose, cold-flow experiments were carried out in the 15 cm i.d. column with coke particles. Pressure fluctuations were measured at 10 cm above the distributor. Two hours after the start of the experiment, addition of water to the bed was started to induce agglomeration. Since the addition of water was larger than the evaporation rate, the *S*-value started to rise and exceeded three after about 13 minutes (see Figure 7). When 4 subsequent *S*-values were larger than three, the water flow was stopped. Then, the water from the bed evaporated and the *S*-value decreased again. After some time, the *S*-value became smaller than three indicating that the original reference situation was restored. Thus, EARS can be used to return to a desired situation when changes are not yet irreversible.

5 CONCLUSIONS

Small-scale bubbling-fluidised-bed gasification experiments have shown that agglomeration can be recognised 20-35 minutes earlier with EARS than with conventional methods based on changes in pressure drop or temperature difference over the bed. The magnitude of this time interval depends on fuel properties and operating conditions, and may well be larger in industrial-scale installations.

Cold-flow experiments have revealed the selectivity of EARS towards agglomeration in that it is insensitive to changes in gas velocity and bed mass up to 10%.

First experiments dedicated to applying EARS for agglomeration *control* have shown that the method is insensitive to simultaneous discharge and make-up of bed material and that EARS can rightly indicate the return to the original state after giving an alarm.

Therefore, the proof of principle has been established of a new monitoring and control method for agglomeration in fluidised-bed combustion and gasification. EARS may help plant operators in preventing agglomeration induced plant shutdowns and minimising bed material make-up and residue production.

Future activities will involve further development of control strategies as well as scale-up and full-scale validation in the 80 MWth wood-fired bubbling-fluidised-bed combustion plant of Essent in Cuijk.

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