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Early Agglomeration Recognition System - EARS

From bench-scale testing to industrial prototype

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Acknowledgement/Preface

This report describes the results for the project "Early Agglomeration Recognition System – EARS" (contract number 2020-01-12-14-003), conducted in the framework of the Novem subsidy programme Renewable Energy in the Netherlands 2001 (Duurzame Energie Nederland, DEN). Novem (currently SenterNovem) is an agency of the Netherlands Ministry of Economic Affairs. The ECN project number was 7.2260.

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Keywords

Biomass combustion/gasification, fluidised bed, agglomeration detection, agglomeration control

Abstract

This report describes the development and testing of a method to monitor and control agglomeration in a bubbling fluidised-bed combustor. EARS - for Early Agglomeration Recognition System - detects agglomeration in an early stage and allows operating staff and engineers to control the agglomeration process and prevent defluidisation.

The project EARS-I was carried out between 15.11.2001 and 29.02.2004. The development was a joint effort of the Energy research Centre of the Netherlands and the Technical University of Delft. The project was carried out together with partner Essent Energie Productie, who installed and hosted the testing of the EARS system in a wood-fired, 80 MW_{th} bubbling fluidised-bed combustor in Cuijk, the Netherlands.

EARS was extensively tested on different bench-scale facilities. EARS was demonstrated to be sensitive to changes in the size distribution as well as the stickiness of particles in the fluidised bed. Both are key parameters in bed agglomeration. For the bench-scale facility a method was developed to control the level of agglomeration in a fluidised bed by means of bed material make-up.

A prototype of the monitoring and control system was tested in the Essent wood-fired, 80 MW_{th} bubbling fluidised-bed combustor in Cuijk, with the aim to develop solutions for typical industrial aspects such as scale-effects, disturbance of other process signals, equipment issues, and process control. A positive relation was found between the *S*-values calculated by EARS and the mass fraction of a particle size considered to be an indicator for the level of agglomeration in the bed. Under industrial conditions EARS is not disturbed by up to 10% variations in the fluidising velocity or bed height. The reliability of EARS was further increased by various techniques, *e.g.* filtering. Prior to a plant stop, EARS was tested and used to support a reduction of the sand make-up rate. A decrease of about 35% was established with minor changes in bed agglomeration. EARS successfully detected the observed changes in the particle size distribution.

Recently, a follow-up project EARS-II was initiated to finalise the design for bubbling fluidised-bed systems and to develop a prototype for circulating fluidised-bed systems.

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SUMMARY

In fluidised-bed combustion and gasification of biomass and waste, agglomeration of bed/ash particles is a major problem. In many cases, bed/ash agglomeration is a self-promoting process which may ultimately lead to complete defluidisation and consequently a forced plant shutdown. With conventional monitoring techniques based on measuring pressure drop or temperature differences, detection is often too late to return to stable operation. To minimise the risk of severe agglomeration it is common practice to refresh the bed material at a relatively high rate, accepting the adverse financial consequences associated with the costs of bed material and residue disposal. Still, however, forced plant outages cannot be prevented completely.

In 2001, ECN and DUT have joined forces to develop a system for agglomeration detection and control in fluidised-bed heat and power generating systems: EARS - Early Agglomeration Recognition System. The objective of this collaboration is to provide a tool which effectively controls agglomeration in industrial applications.

The work covered in this report was carried out within the project EARS-I, between 15.11.2001 and 29.02.2004. The project was carried out together with partner Essent Energie Productie, who purchased and installed the necessary equipment for EARS and collaborated in the industrial testing of EARS. Results from both small-scale, conceptual tests and industrial testing are discussed.

EARS – Proof of principle and proof of concept

EARS employs the continuous measurement of in-bed high-frequency pressure fluctuations to detect significant changes in the fluid dynamic behaviour of a fluidised bed. Non-linear analysis techniques are used to calculate a statistic value, *S*, which compares the bed's actual behaviour to a known, stable reference period.

EARS was extensively tested on bench-scale facilities. In a bubbling fluidised-bed gasifier/combustor it was demonstrated to detect agglomeration 30-60 minutes earlier than the more conventional techniques can detect it. In addition, it was shown that EARS is insensitive to <10% variations in fluidising velocity and bed height as encountered in industrial practice. On the other hand, EARS was demonstrated to be sensitive to changes in the size distribution as well as the stickiness of particles in the fluidised bed, both of which are key parameters in fluidised-bed agglomeration.

While agglomeration problems can be potentially lifted by a temporary reduction of thermal load or increase of fluidising velocity, a more continuous and lasting effect is to be expected from controlling the replacement of spent bed material by fresh sand. Therefore, modifications were made to the bench-scale facility to test this method of agglomeration control. Although the effectiveness was somewhat limited at the small scale of the tests, the concept to control the bed quality or agglomeration status by means of sand make-up based on the detection by EARS was without doubt proven successful.

EARS – Industrial prototype

At the Essent wood-fired, 80 MW_{th} bubbling fluidised-bed combustor in Cuijk (NL), an EARS prototype was installed. Six measurement points were built into the combustor to cover the entire fluidised-bed surface. Extensive measurements were recorded together with relevant process data and analyses of bed material samples collected in selected periods.

Initial practical problems with the design and operation of the pressure measurement probes were overcome by improving the purge system to prevent the probes from plugging, and an improved design for the mechanical protection of the probes. Substantial efforts have been made to evaluate the EARS signals against recorded process data and bed material analyses. As in the bench-scale tests, EARS was again shown to be insensitive to <10% changes in either bed height or fluidising velocity (here: primary air flow). A positive relation was found between the process value calculated by EARS and the mass fraction of particles larger than a certain size considered an indicator for the level of agglomeration in the bed. No correlation was found with other process data.

In order to cope with normal process variations - operator-induced or not - which may have an unknown, but significant impact on the fluid dynamics of the bed, a new technique was developed. The technique works very well for relatively large and slow variations such as those which might be brought about by a change of fuel quality and which bring the process to another working point. Although it would be possible to develop a ‘library’ of typical working points, this would complicate using EARS. The new technique uses a moving or dynamic reference period with a constant time lag between the evaluation and the reference time series. In this way the system automatically adjusts to the new operating conditions. Obviously a careful, process-dependent selection of the time lag is crucial for the timely detection of problematic agglomeration.

Using the newly gained knowledge, a final EARS prototype was prepared for testing during a one-week period prior to a planned maintenance stop of the power plant. In the test programme a reduction of the normal sand make-up was planned. As a part of the prototype, an instruction set was developed to control agglomeration using the EARS detection system. The monitoring software was modified accordingly and given an interface including warning and alarm level indications.
During the test week a 35% reduction of the sand make up was accomplished. Although no fluidisation problems were detected, a deterioration of the bed quality in terms of the coarse particle fraction was confirmed. EARS successfully detected this change of particle size distribution by the generation of an alarm.
An algorithm to control the bed discharge and sand make up rates based on the EARS’ *S*-values was proposed but not tested in practice, because the quality of the pressure measurements was insufficient at the time of the test. A proper control of the functioning of the pressure measurement probes is essential for continuous monitoring of the agglomeration status.

In order to control agglomeration effectively, the process control algorithm must be validated in practice such that the proposed criteria for warning and alarm can be optimised. It should be noticed though, that for the Essent fluidised-bed combustor, due to the installation of an automated sieve for bed quality control, EARS is to be regarded as the second(ary) control system for agglomeration.

Outlook

Recently, a follow-up project EARS-II was initiated to finalise the design for bubbling fluidised-bed systems and to extend the application of EARS to circulating fluidised-bed systems.

1. INTRODUCTION

1.1 Background

In fluidised-bed combustion and gasification of biomass and waste, agglomeration of bed/ash particles is a major problem. In many cases, this bed/ash agglomeration is a self-promoting process. At the onset of agglomeration, the fluidisation behaviour gets disturbed due to, *e.g.*, the formation of particle clusters (Figure 1.1) 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 to return to stable operation. So, to minimise the risk of severe agglomeration it is common practice to refresh the bed material at a relatively high rate, accepting the adverse financial consequences associated with the costs of bed material and residue disposal. Still, however, forced plant outages cannot be prevented completely.

In 2001, ECN and DUT have joined forces to develop a system for agglomeration detection and control in fluidised-bed heat and power generating systems: EARS - Early Agglomeration Recognition System. The objective of the work is to provide a tool which effectively controls agglomeration with minimum requirements to the process, safeguarding economically sound process operation. The evolving technique EARS has been successfully demonstrated on a lab-scale [1,2,3] and was installed for testing in the Essent wood-fired, 80 MW_{th} fluidised-bed combustor in 2002 (Figure 1.2). This report presents the results of conceptual and industrial testing.

Figure 1.1 *Initial agglomerate of sand particles.*

Figure 1.2 *80 MW_{th} wood-fired BFB boiler in Cuijk, NL.*

1.1.1 Detection and control of agglomeration

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 [1,2,3] 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 has 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 (until now defined as 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.

1.1.2 EARS principles

The core of EARS is the attractor comparison method, developed at Delft University of Technology by Van Ommen *et al.* (2000). The attractor comparison method compares pressure time-series in a statistical way using non-linear analysis techniques. 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 (defined as evaluation time-series) are measured. The comparison of reference and evaluation time-series can be done by considering a single property of the time-series, but it is well possible that the nature of the time-series changes while that specific property remains unaffected. Therefore, we have finally chosen to compare the time-series as a whole using attractor reconstruction. The only property we exclude from comparison is the standard deviation of both time-series to reduce the sensitivity to the superficial gas velocity. 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 1.3a). The attractor represents consecutive states of the dynamic system: it can be seen as a ‘fingerprint’ of the fluidised bed hydrodynamics as reflected by the pressure fluctuations in the bed. The reference attractor and the evaluation attractor are compared by calculating a statistic *S* using non-linear analysis techniques [4] (see Figure 1.3b). *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.

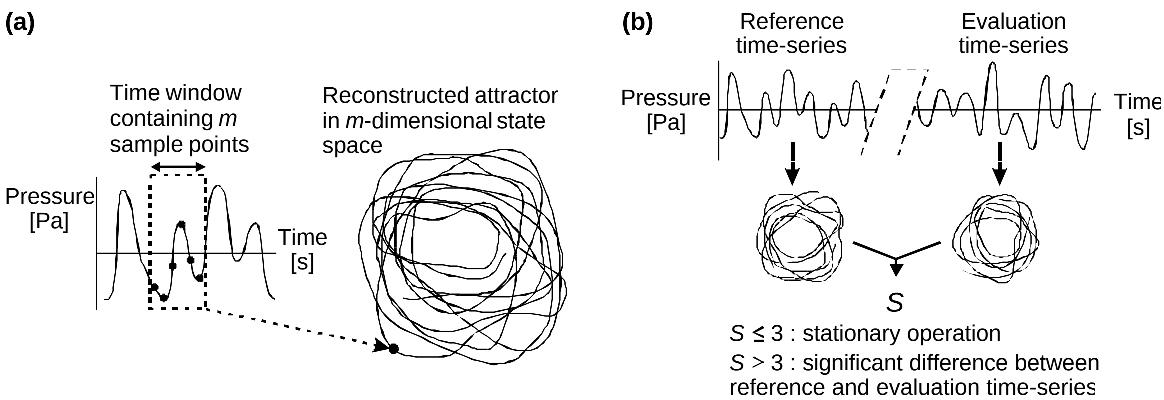


Figure 1.3 *Schematic representation of **(a)** the reconstruction of an attractor from a pressure fluctuation signal, and **(b)** the comparison of attractors by the monitoring method.*

1.2 Objectives

The objective for this work was to develop EARS for the detection and control of agglomeration in industrial fluidised bed systems for biomass conversion. Specifically, the project aimed to:

- develop an agglomeration detection system for industrial application
- generate the knowledge to correlate the detection system output with the actual bed agglomeration status
- develop appropriate strategies for agglomeration control
- demonstrate that EARS improves the control of agglomeration.

2. EARS - PROOF OF PRINCIPLE AND CONCEPT

2.1 Early detection of agglomeration on a bench-scale

It had been shown in several bench-scale tests [1,2,3] that EARS effectively detects agglomeration, half to one hour *before* the more conventional techniques based on pressure or temperature difference do. An example of such a test result is given in Figure 2.1.

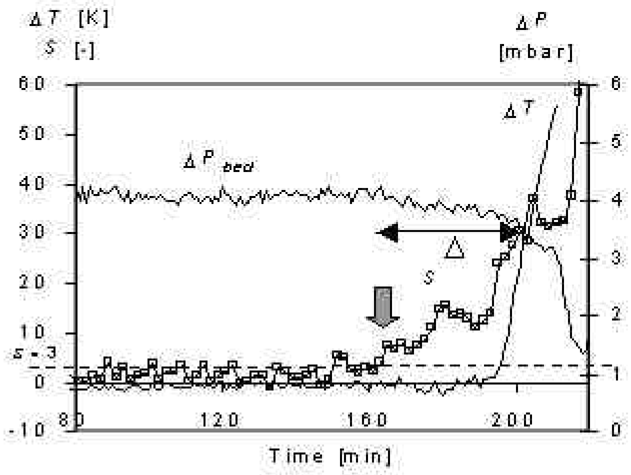


Figure 2.1 *The effectiveness of EARS is demonstrated in a bench-scale miscanthus gasification test at 760°C [3].*

In this test, miscanthus fuel was gasified in a bench-scale bubbling-bed gasifier at a constant temperature of 760 °C. Fuel was fed continuously into a 1 kg sand bed (d_p 340 µm) without bed material discharge, until defluidisation occurred. In addition to the EARS system, conventional in-bed pressure drop and temperature difference measurements were collected for comparison. From Figure 2.1 it can be seen that both the in-bed pressure drop and the temperature difference react to changes in the system just before t=200 min. Although the response of the temperature difference is somewhat faster than the pressure drop, both do not show a response until the bed is nearly defluidised. In contrast to these, EARS is shown to be much more sensitive; a significant response is obtained just after t=165 min, indicating that the fluid dynamic behaviour of the bed has changed compared to the start of the experiment.

In the next section, test results are reported to discuss how, and to which extent the fluidised bed dynamics influence the EARS detection mehod.

2.2 Sensitivity and selectivity

2.2.1 Cold testing in model systems

Cold-flow experiments with changes in gas velocity, bed mass and purge flow through the pressure probes, 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.
For the changes in gas velocity and bed mass, the local pressure in the bed was measured using probes with a length of 10–60 cm and an internal diameter of 4 mm. To test the functionality and performance of the pressure probes installed in the Essent combustor, purge flow experiments where executed with both, horizontal connected probes and probes connected under an angle of 45^o. Both probes were 60 cm long and had an internal diameter of 10 mm. The purge flow was controlled with a mass flow controller.

Piezoelectric pressure sensors of Kistler type 7261 connected to the probes were used to measure the pressure fluctuations. The pressure drop over the fluidised bed was measured with a Validyne DP15 reluctance differential pressure transducer. 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-bit analogue-to-digital conversion was applied at a sample frequency of 200 or 400 Hz.
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 normalized and the probes are positioned approximately halfway the gas distributor plate and the bed surface. 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 2.2 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.
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 2.3 shows that the *S*-value stays below 3 for all bed mass changes smaller than 10%.

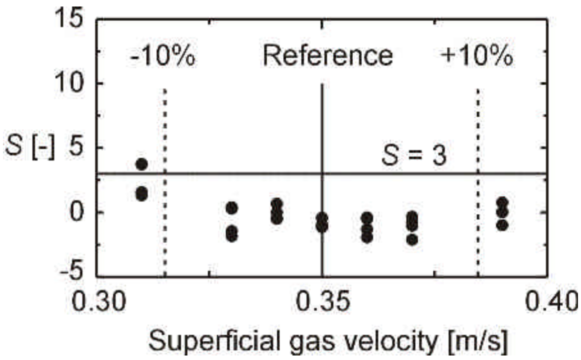


Figure 2.2 *Influence of the superficial gas velocity on the S-value.*

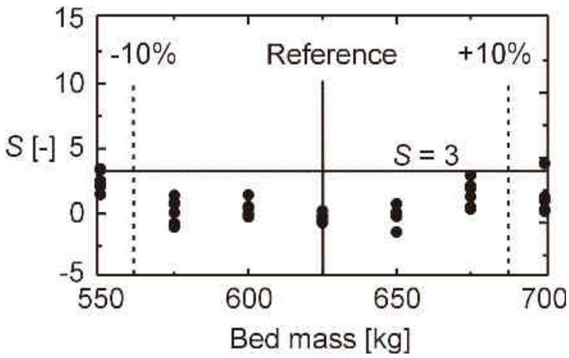


Figure 2.3 *Influence of the bed mass on the S-value.*

For the purge flow experiments the column was operated at a superficial gas velocity of 0.44 and 1 m/s. One hour pressure fluctuations time series were recorded for purge flows varying from 8 to 0.5 m/s. Power Spectral Density (PSD) analyses of the pressure fluctuation measurements, as shown in Figure 2.4, indicated that the purge flow has no crucial negative influence on the pressure fluctuation measurements. Additionally the analysis indicates that at purge flows above the 1 m/s, no sand is trapped or flows into the probes. These tests point out that, under process conditions as used in the Essent combustor, 'safe' purge flow conditions to prevent blocking of the pressure probes, can be established with velocities of around 2 m/s or higher.

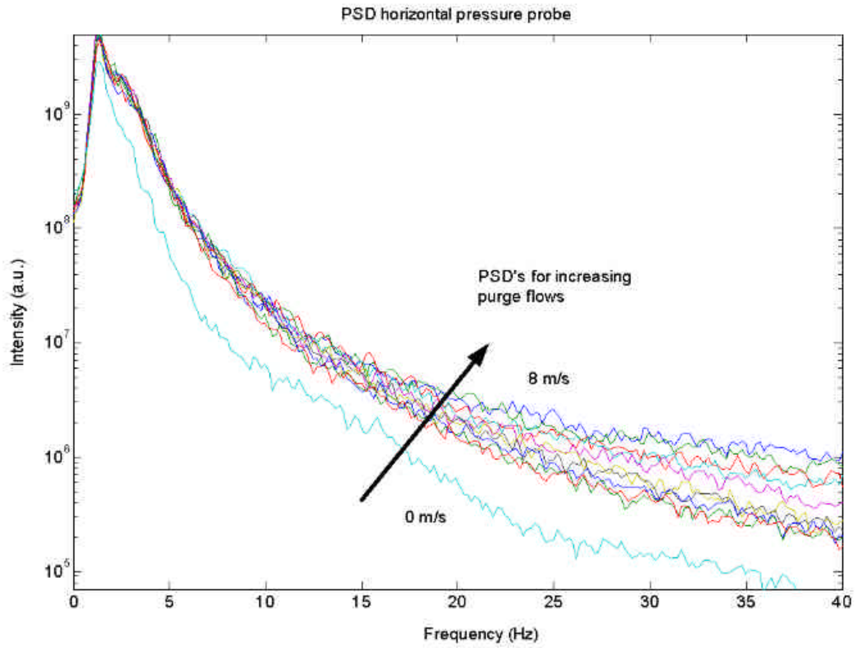


Figure 2.4 *Example PSD analysis of pressure fluctuation measurements at varying purge flows.*

2.2.2 Hot testing in agglomerating systems

To determine the effectiveness and selectivity of EARS, bench-scale gasification and combustion tests were conducted. The bench-scale tests were carried out in a 7.4 cm i.d. bubbling-fluidised-bed gasifier/combustor shown schematically in Figure 2.5.

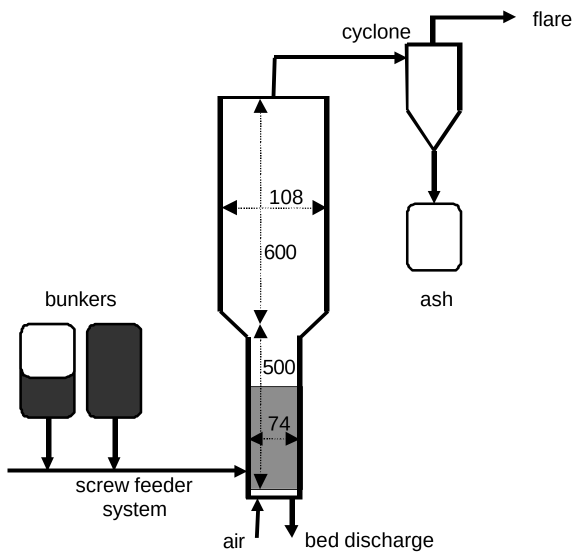


Figure 2.5 *Schematic representation of the 1 kg/h bubbling-fluidised-bed gasifier/ combustor, sizes in mm.*

To further identify the relation between the measured *S*-value and the actual state of agglomeration in the bed, agglomeration tests were performed while relevant properties of the bed material were evaluated. Properties investigated included average particle size, sphericity and the minimum fluidising velocity (low and high temperature) of the spent bed material. In the tests, clean wood chips provided by Essent as fired in their 80 MW_{th} BFB combustor were milled and combusted at a temperature of 850 °C. The fuel was fed at a rate of 0.6-0.7 kg/hr into

a 1 kilogram sand bed (particle size range 0.8-1.2 mm, with a mean diameter of 956 µm). The fuel entrance was either in-bed (screw feeding) or over-bed (gravimetric feeding), the latter to simulate the feeding system of the Essent 80 MW_{th} BFB combustor. As a general observation, over-bed feeding resulted in higher freeboard temperatures, which enhanced the deposition of sticky bed particles at the reactor wall, at the bed-freeboard interface. At this small scale of testing, this wall-effect interferes with a clean interpretation of the experiments and, therefore, over-bed feeding was abandoned for the tests reported here.
The sand bed was fluidised at approximately 1 m/s (850 °C) to resemble the conditions of the Essent BFB combustor. Bed samples were collected every now and then through a tube protruding the air distributor plate. Selected bed samples were transferred to a simplified, electrically heated quartz fluidised bed facility to determine their fluidising properties.
In all experiments, local pressure fluctuations were measured in the bed as the raw input data for EARS. Probes with a length of 50 cm and an internal diameter of 4 mm were used to guarantee an undisturbed transfer of the signal in the frequency range of interest [5]. In the gasification/combustion tests, a purge flow was used to prevent particles from blocking the probe. Piezoelectric pressure sensors of Kistler type 7261 connected to the cold side of the probe picked up the in-bed 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.

Table 2.1 summarizes the main combustion tests carried out in the ECN bench-scale facility. For comparison, Table 2.2 summarizes the main parameters for the Essent 80 MW_{th} BFB combustor.

Table 2.1 *Main parameters of tests carried out in bench-scale bubbling bed combustor/ gasifier.*

Fuel	Wood	Wood	Wood+bark	Wood+cocoa shells
Test no.	1 2 3	4	5	6
Date	090402 230502 270502	280602	240402	110402
Combustion (C) / gasification (G)	C	C	C	C
Purpose	test normal operation duration test – 5% O2 duration test – 0.8% O2	over-bed feeding	influence sec. fuel	influence sec. fuel
Bed material	Sand, 956 µm	Sand, 940 µm	Sand, 956 µm	Sand, 956 µm
Fuel feed rate [g/hr]	675 (4% moisture)		380+180 (4% moisture)	523+53 (4% moisture)
Fuel size [mm]	0.7 - 2.0	0.7-2.0	0.7 - 2.0	0.7 - 2.0
Air flow rate [nl/min]	95 70 50	70	95	95
N2 flow rate [nl/min]	- 25 45	25	-	-
Lambda [-]	1.9 1.4 1.0	1.4		
Temperature [°C]	850	850	800 - 900	850
Φm [kg/(kg sand . hr)]	0.66		0.54	0.56
Φth [kW/kg sand]	3.3		ca. 2.7	ca. 2.8
Φth [kW/m^2 bed]	770		ca. 630	ca. 650

Table 2.2 *Main parameters 80 MW_{th} BFB combustor*

Fuel	Wood
Bed material	Sand, 956 µm
Fuel feed rate [tonne/hr]	30 (40% moisture)
Fuel size [mm]	20 - 50
Primary air flow rate [nm^3/s]	8.6
Secondary air flow rate [nm^3/s]	21
Primary lambda [-]	0.37
Overall lambda [-]	1.27 (4% O_2)
Temperature [°C]	850
Φm [kg/(kg sand . hr)]	1.0 (at 29 ktonne sand in bed)
Φth [kW/kg sand]	3.3 (at 29 ktonne sand in bed)
Φth [kW/m^2 bed]	2470
U_0/U_{mf} [-]	ca. 3 (@ 0.9 m/s)

Test no. 1 was carried out to establish stable operating conditions for the bench-scale combustor using the Essent bed sand and fuel. The settings and conditions found suitable were used in subsequent experiments, as listed in Table 2.1.

In tests no. 2 and 3 the combustor was operated for two days each, maintaining as stable conditions as possible. The oxygen/fuel ratio was varied between the tests to evaluate the relevance of this parameter for the agglomeration process, knowing that air staging is also applied in the 80 MW_{th} combustor (see Table 2.2).
The results of these two tests are plotted in Figures 2.6 and 2.7, giving the *S*-value as a function of time. From the tests the following observations were made:

- First, a procedure was tested for the on-line sampling of bed material for analytical purposes. Samples were withdrawn from the bed by shortly opening a valve connected to a 8 mm ID tube in the air distributor plate and. Directly after, an equivalent amount of fresh sand was added to the bed from above. If 80 grams of bed material are replaced in this way, the changes in bed mass are detected by EARS, as can be seen from Figure 2.6 (second arrow). After the replacement procedure however, the *S*-value returns to the level before sampling. Further testing with smaller amounts of bed material withdrawn showed an even negligible effect on the *S*-value (e.g., first and third arrow in Figure 2.6). All additional testing has been carried out taking small (approximately 60-70 gram) samples.
- Comparing the *S*-trends of both tests it appears that the monitored fluidisation behaviour changes in a much similar way. There were no indications for a large influence of the oxygen/fuel ratio. In both cases, a gradual increase of the *S*-value is observed in time. For these experiments, a maximum value around 9 was found. The smooth increase of S, together with the failure of any deviations in bed pressures and temperatures seems to indicate that the properties of the bed material are slowly changing. During neither of the tests did the bed agglomerate severely. At the end of both duration experiments about 800-900 gram of the original 1000 gram was retrieved. Some of the remaining material was found to stick to the reactor wall at the bed-freeboard interface, while some was elutriated.

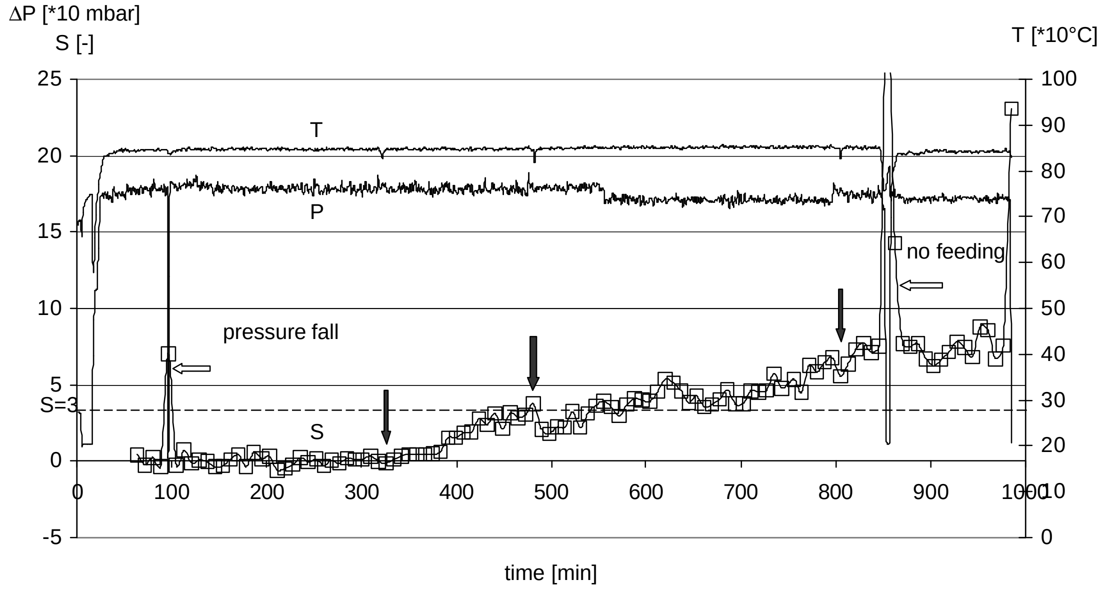


Figure 2.6 *Calculated S-value during wood combustion test at 850 °C and 5% excess oxygen. The black arrows indicate the replacement of bed material.*

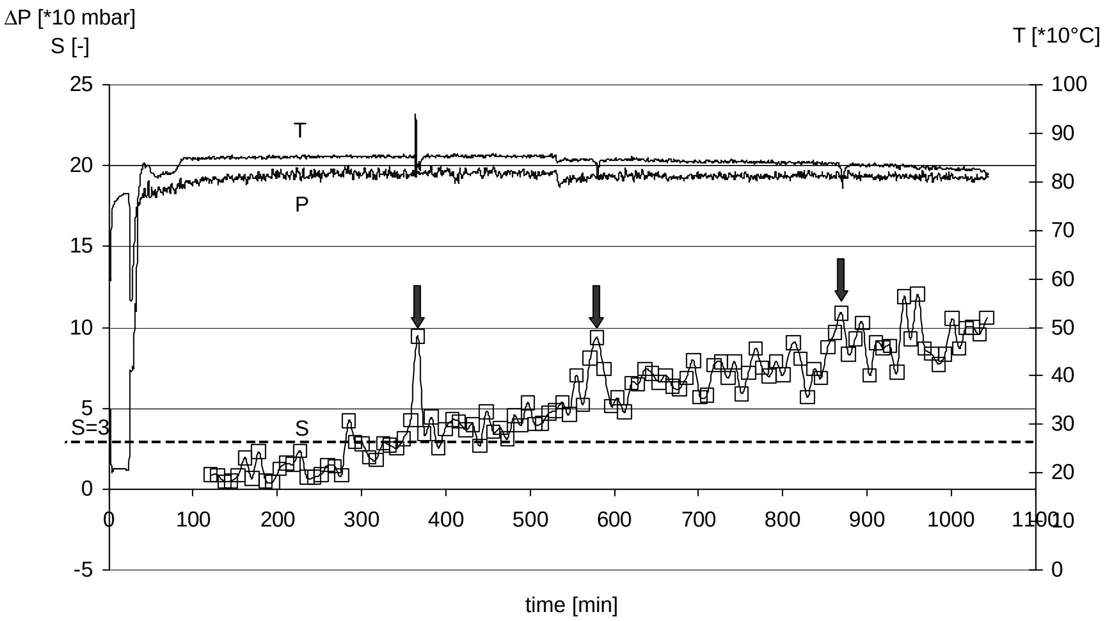


Figure 2.7 *Calculated S-value during wood combustion test at 850°C and 1% excess oxygen. The black arrows indicate the replacement of bed material.*

Table 2.3 *Properties of bed material after combustion test.*

Test No.	d_p [µm]	ρ_s [1] [g/cm^3]	ε_{mf} [-]	U_{mf} [2] [m/s]	Φ_s [-]
blanc	956	2.58	0.45	0.50	0.75
1	885	n.d.	0.46	0.53	0.83
2	935	2.56	0.43	0.63	0.90
3	951	n.d.	0.45	0.58	0.86
4	540	2.57	0.50	0.31	0.73
5	925	n.d.	0.45	0.54	0.85
6	939	n.d.	0.46	0.53	0.83

[1] helium pycnometry measurement
[2] at room temperature

Considering the insensitivity of EARS for small changes of the particle size distribution as described in section 2.2.1, and the fact that just a small number of initial agglomerates of a few sand grains sticking together were found in the bed samples, the observed *S*-trends could not be explained by the formation of these initial agglomerates. On the contrary, sieving analyses indicated that the mean particle size had actually decreased (Table 2.3). The sphericity of the particles had increased, indicating that sharp edges of the fresh sand were either abraded due to the fluidisation, or smoothed by the formation of fluid coatings.

From Table 2.3 it is seen that, in all cases, the minimum fluidising velocity U_{mf} (cold) increases. The duration of tests no. 1, 5 and 6 was approximately half the duration of tests no. 2 and 3 (500 versus 1000 minutes), which indicates a time dependency. Neither the decrease of the mean particle size, nor ε_{mf} or ρ_s can account for the observed increase of U_{mf} and must be attributed to an increase of the particle sphericity, Φ_s. In principle, Φ_s is expected to increase when the edges of sharp particles such as in fresh sand are worn by friction (=attrition). However, additional fluidisation tests carried out using the same sand at both room temperature and at 800 °C, delete attrition as a major mechanism for erosion because no change in the minimum fluidising velocity was detected after 900, resp. 200 minutes of continuous fluidisation. A more likely mechanism is the one that attributes the increased Φ_s to the smoothing effect of the ash coating that builds up on the rough surface of the sand particles, as can be seen from Figure 2.8. These SEM micrographs not only show a biomass derived ash coating, but the micrograph to the right also reveals the presence of multiple cracks in the interior of the sand particle. The latter represents how bed particles that have been subjected to industrial conditions - *i.e.* high heating rates and local temperature fluctuations - look like. This material was used as the starting bed material for test no. 4, whereas in the other tests fresh sand was used. Based on the observations, particle fragmentation seems to be the more likely dominating eroding mechanism rather than attrition. Moreover, fragmentation also explains the *decrease* of Φ_s specifically in test 4, contrary to the other tests.

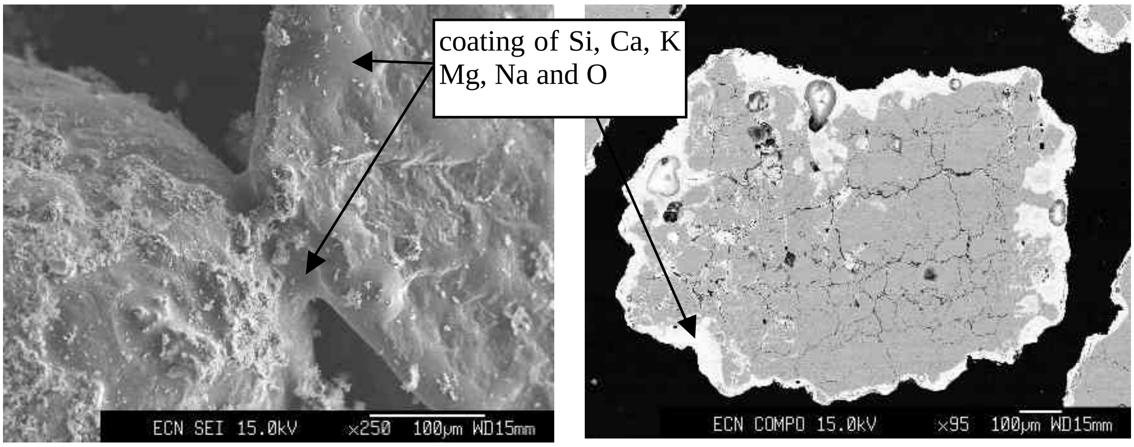


Figure 2.8 *SEM micrographs of bed particles showing biomass ash-derived coating (left and right) and internal cracks (right). The left micrograph was obtained from test no. 2, the right was obtained from spent bed material*.

The results so far indicate that building up an ash coating and particle fragmentation are both mechanisms which may significantly influence the fluidising properties of the bed material in terms of F_s and thereby U_{mf}. Since U_{mf} increased by more than 10% in tests 2 and 3, and fragmentation was insignificant (see d_p), for these tests it seems valid to conclude that the coating effect on F_s by itself causes S to exceed the threshold value three. The fact that the highest F_s values are found in the tests with the longest duration suggests that the process of coating the particles with an ash layer continued for quite a long time, *i.e.* between 500 and 1000 minutes.
In tests no. 1, 5 and 6, U_{mf} increased by less than 10%, whereas S-values in the range of 5-8 were measured. Here, only the high temperature effect of particle stickiness can explain the observed increase. To investigate the relation between S and the stickiness of fluidised particles, additional tests were carried out. For these tests, various spent bed materials were fluidised in a 5 cm ID electrically heated reactor.

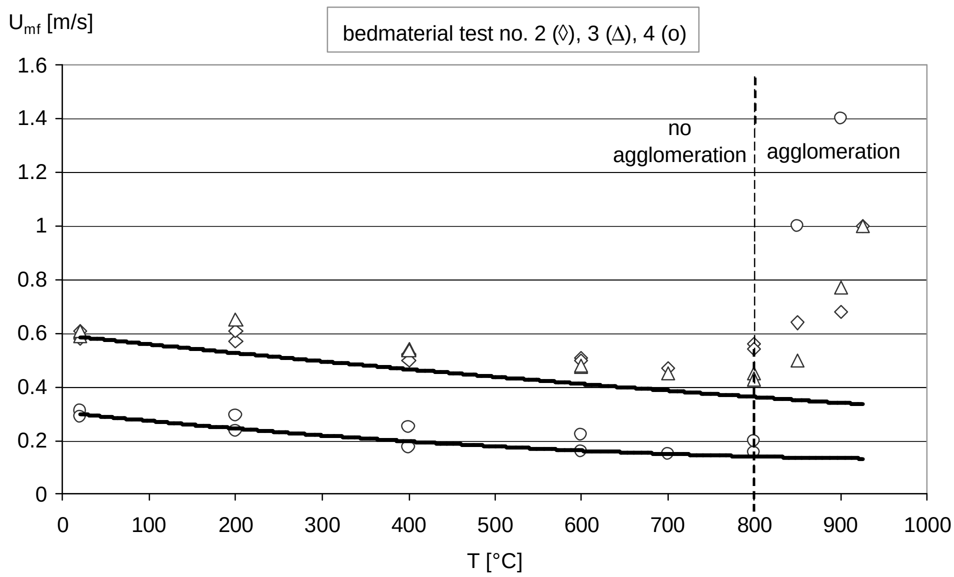


Figure 2.9 *Minimum fluidising velocity determined as a function of temperature. The lines represent calculated values.*

The temperature of the fluidised bed was increased in the range 20-1000 °C, and at each temperature the minimum fluidising velocity was determined. It was found that the experimentally determined minimum fluidising velocity followed the theoretical one up to approximately 700 °C (see Figure 2.9). Above 700 °C, and specifically above 850 °C - a typical temperature for fluidised-bed combustors - the experimental values became increasingly larger than the theoretical ones. In all cases, the bed defluidised at a temperature close to 930 °C. Just before this point, the experimental minimum fluidising velocity had increased to values up to six times the theoretical value. The difference between the experimental and theoretical values is due to the stickiness of the glassy coating on the bed particles. Above 800 °C the coating starts to develop a viscosity which is low enough to cause an individual particle to stick (longer) to its neighbouring particles. As a result, more energy and thus a higher fluidising velocity is required to fluidise the particles. The stickiness increases up to a temperature where agglomerated particles are no longer separated by the momentum of the gas flow, and the fluidised bed can no longer be sustained; the bed defluidises.

To demonstrate the sensitivity of EARS for coating-induced particle stickiness, a number of high-temperature fluidising tests was carried out with coated bed material, using the same electrically heated reactor. After heating to 600 °C the bed was fluidised at twice the minimum fluidising velocity during 10 minutes. The bed was then further heated to 775 °C, while keeping the relevant gas properties constant. The superficial gas velocity was kept constant by adjusting the gas mass flow to the temperature-induced density change, and the change in gas viscosity was compensated by mixing argon with the fluidising air. The results plotted in Figure 2.10 show that the fluidisation behavior expressed by the *S*-value was not yet significantly changed by this temperature increase.

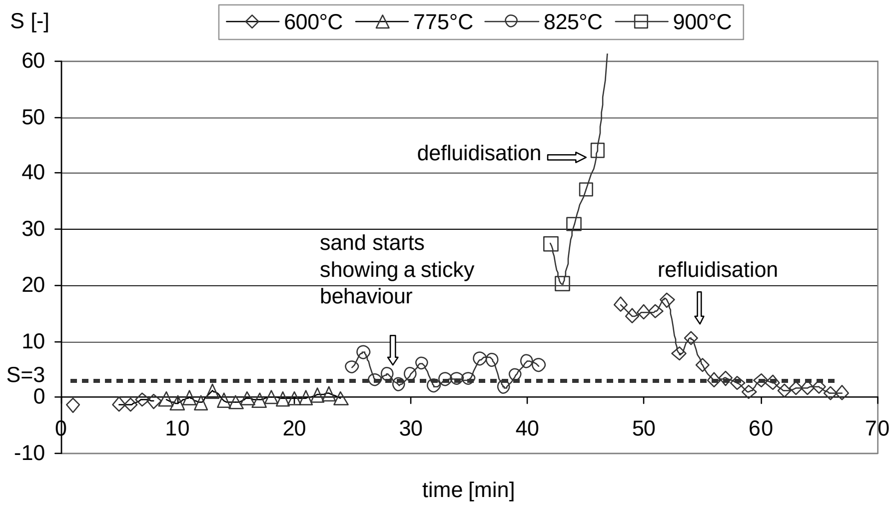


Figure 2.10 *The influence of particle stickiness on fluidisation behaviour, demonstrated by measuring the S-value of a fluidised bed of ash-coated (spent) particles at typical coating melt temperatures (see also Figure 2.9).*

This was expected considering the small difference between the experimental and theoretical minimum fluidising velocity at 775°C (Figure 2.9), indicating that stickiness is not relevant at this temperature. When the temperature was additionally increased to 825 °C the *S*-value exceeded 3, which, considering Figure 2.10 again, demonstrates the effect of particle stickiness on the *S*-value. Further heating to 900 °C caused the bed to defluidise, causing the *S*-value to run away. When the bed was cooled down to 600 °C, it was eventually refluidised. The *S*-value recovered correspondingly.

To determine whether the *S*-value depends on particle shape (Φ_s), some additional fluidisation experiments where carried out. Different bed materials - fresh sand, spent bed material from bench-scale test no.2, and bed material from the 80 MW_{th} plant - were sieved and then identical particle size distributions were composed: 75% 710-1000 µm and 25 % 1000-1250 µm. The bed materials were fluidised and the fluidisation behaviour in terms of measured *S*-values are compared in Figure 2.11. The figure shows significant differences between the three bed materials with varying particle sphericity.

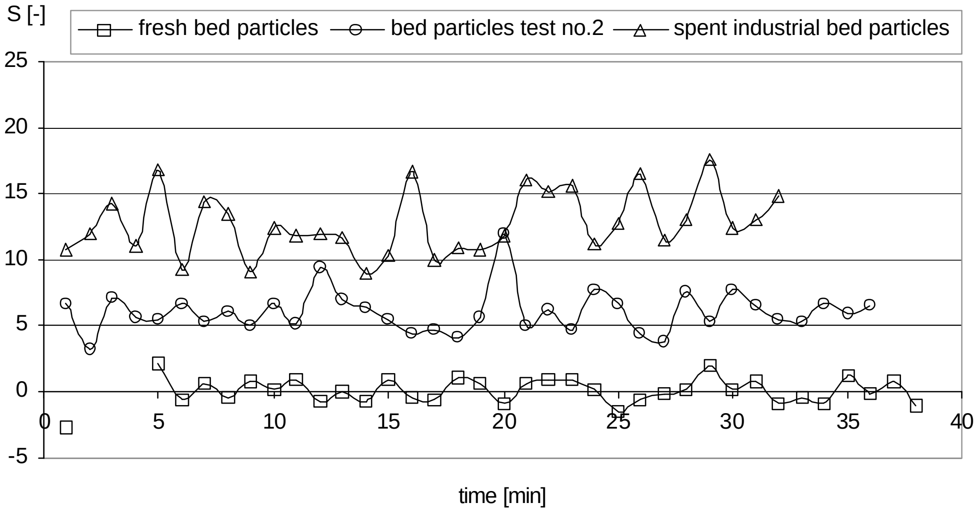


Figure 2.11 *S-values measured with different bed materials having the same particle size distribution and density but different particle sphericity.*

An important conclusion from this work is that it has now been shown that the monitoring method is sensitive enough to detect increased particle stickiness, even *before* multi-particle agglomerates have actually been formed. This demonstrates the inherent superiority of the method over, *e.g.* ΔT or Δp based methods which detect phenomena that influence the bed's macro-behaviour, usually as a result of agglomerate formation in progress.

2.3 Agglomeration control

2.3.1 Reversibility of *S*-value

To investigate if EARS can correctly indicate the return to the original state after giving an alarm, 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. As 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 2.12). When four subsequent *S*-values were larger than three, the water flow was stopped and the bed temperature was raised from 20^{o}C to 35^{o}C. When the water from the bed had evaporated and the *S*-value decreased again, the temperature was set to the original value. After some time, the *S*-value became smaller than three indicating that the original reference situation was restored. Both experiments, namely with different bed mass and water drop flows, show similar results. Thus, EARS can indeed be used to return to a desired situation when changes are not yet irreversible.

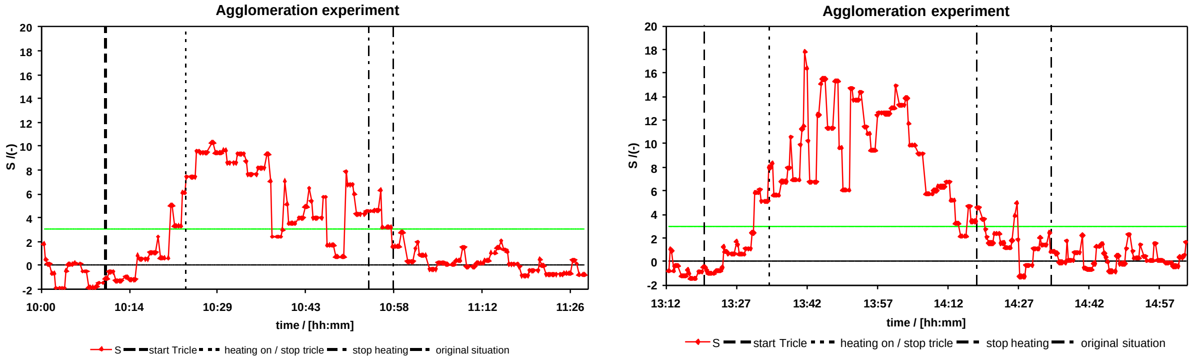


Figure 2.12 *Agglomeration experiments with a bed of 3.6 kg and water flow rate of 6.5 ml/min. Both experiments illustrate the recovery from an agglomeration warning.*

2.3.2 Bench-scale testing

The attractor comparison method is also suited for process control, *i.e.*, once the monitored process has significantly deviated (*S*>3) from a stable reference, the *S*-value can in fact be used to monitor the return of the process to the reference conditions [3]. Recently two tests were carried out in a 1-kg/h bubbling-fluidised-bed facility to demonstrate EARS as a method for detection *and* control of agglomeration in fluidised bed combustion of biomass. The facility was described in section 2.2.2. Fuel type and feed rate, fuel/air ratio, starting bed material type and mass, and bed temperature were identical in both tests. In the first test, the ash produced from the fuel was allowed to accumulate in the bed without any discharge of bed material for a period of seven hours. The *S*-value as well as the bed temperature and pressure drop are plotted in Figure 2.13. In the second test the *S*-value served as a process value to suppress agglomeration phenomena by means of bed material replacement. The results of the second tests are plotted in Figure 2.14.

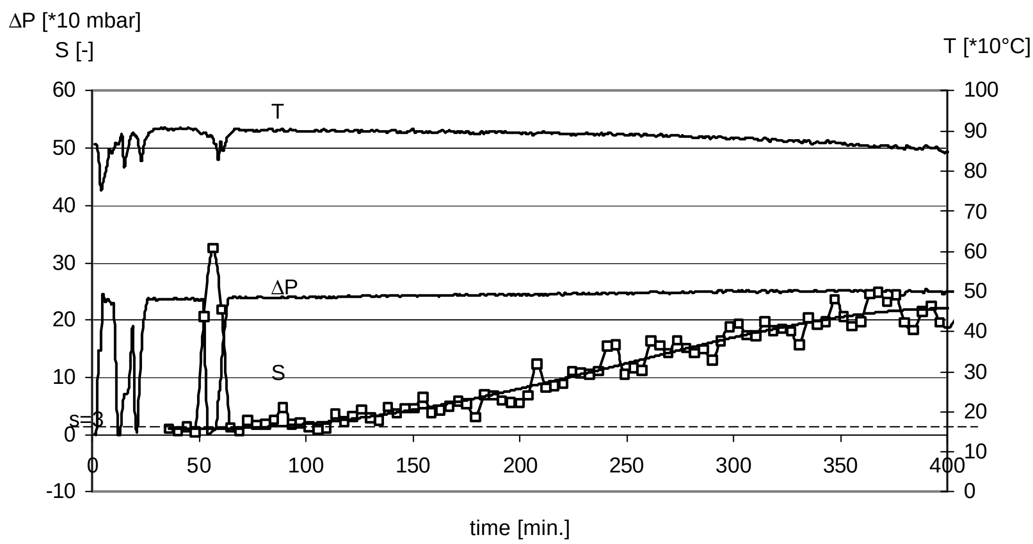


Figure 2.13 *The S-value measured during a seven hour test in which a 90/10 (m/m) mix of wood and an agglomeration-sensitive fuel was combusted in a bench-scale fluidised bed reactor. The biomass ash was allowed to accumulate.*

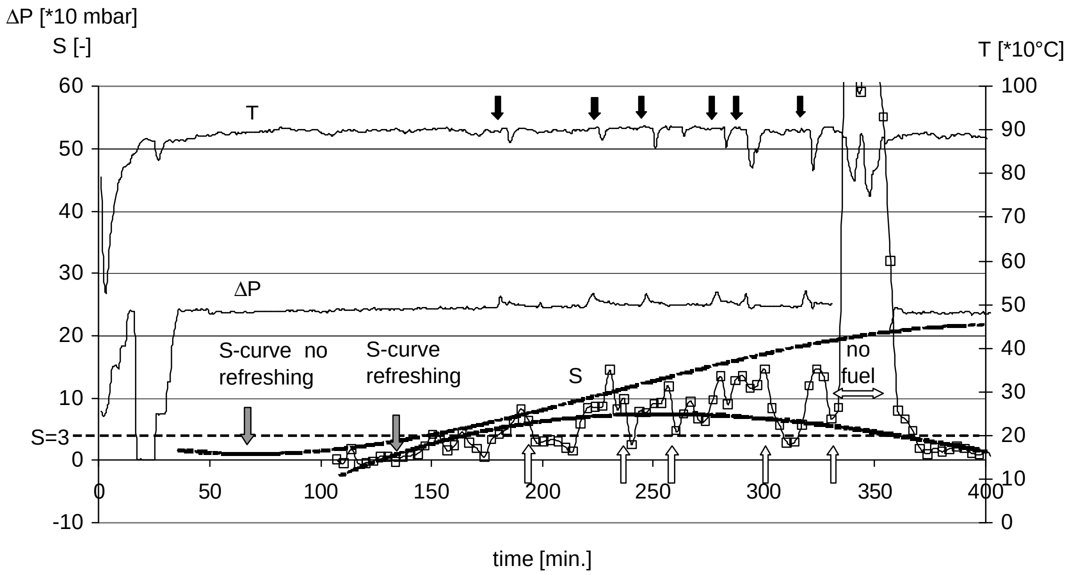


Figure 2.14 *The S-value measured during a similar, seven hour combustion test. Periodically, a small part of the bed material was discharged and replaced by fresh (uncoated) sand. The black arrows indicate the replacement of bed material, while the open arrows indicate the reaction of the S-value.*

In both tests the combustion process as well as the average bed properties were stable given the fact that no significant variations in the bed temperature and pressure drop are observed. In the second test, at S>3, approximately 8% of the bed material (<10% of total bed mass) was replaced by fresh sand. In both tests the *S*-value exceeds the value 3 after approximately 2 hours of stable operation. Inspection of the bed material (at the end of the first test, and intermediate samples of the second test) revealed that few agglomerates had formed, but neither test had lead to severe agglomeration. Inspection of the reactor internals at the end of each test revealed build-up of sticky bed particles at the reactor wall. This was found predominantly at or above the level of the bed surface, where particles can reside at the wall without being mechanically removed by the fluidised bed. As a result, the bed mass decreased during the test which, in turn, will probably have influenced the *S*-value in addition to the formation of sticky particles and initial, small agglomerates.

The decrease of bed mass in the second test was compensated for by replacing each discharged batch of bed material by 120% of fresh sand. The 20% surplus needed to maintain a constant bed mass was estimated from the bed pressure drop, and the estimate was verified by comparison of the starting and final bed mass. The second test unambiguously demonstrates the beneficial effect of bed material replacement. Each time spent bed material is replaced by fresh sand the *S*-value returns to a value close to 3 within 5-15 minutes. Nevertheless, as the coating of the sand particles continues, the bed inventory as a whole developes an increasing, average stickiness. The effect of freshly added sand on the average stickiness is limited and diminishes as the average stickiness increases. As a result, the rate of bed material replacement required to maintain the *S*-value at a setpoint, increases. The overall replacement of some 48% of the bed material in seven hours has successfully suppressed the average stickiness of the bed inventory as can be concluded from the much lower average *S*-value in the second test (Figure 2.14).

3. EARS - INDUSTRIAL PROTOTYPE

3.1 Set-up and operation of measurement system

In 2002 a basic EARS version was installed in an 80 MW_{th} bubbling fluidised-bed wood combustor. The objective was to develop a prototype addressing the following specific issues:

(1) Reliable detection of agglomeration in an industrial environment.
(2) Effective agglomeration control strategies.

The industrial prototype including manual process control instructions was tested as a part of the programme.

3.1.1 Set-up of the system

The first requirement for reliable industrial agglomeration detection concerns instrumentation. Based on previous experience in the bubbling fluidised-bed heat exchanger of an industrial circulating fluidised-bed combustor [1], a combination of a gas-purged measurement probe and a sensitive, high frequency piezoelectric pressure sensor with data-acquisition equipment was used. In principle, the probe is installed in the fluidised bed, the pressure sensor just outside, and the system for data-aquisition and data processing is placed in the control room. The set-up of the measurement probes installed in the 80 MW_{th} combustor is shown in Figure 3.1.

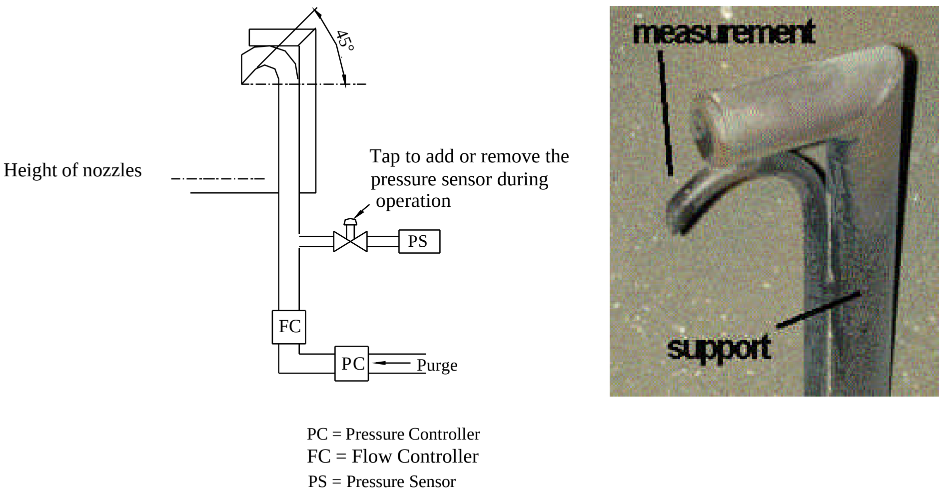


Figure 3.1 *Set-up of the probe for pressure measurements. To the right: photo of initial design for the 80 MW_{th} fluidised-bed combustor.*

The probe protrudes vertically through the bottom of the fluidised bed. A purge flow must be applied to prevent clogging. Background information on the pressure measurement requirements can be found elsewhere [5]. The measurement probe must be mechanically supported to withstand the forces exerted by the surrounding bed mass. The support shown by the photo in Figure 3.1 was later replaced by a protective construction around the probe.

The measurement technique used here has a typical depth of vision of 0.5-1 m. For industrial installations requiring complete coverage of the bed surface area multiple probes and sensors are needed. In the 80 MWth combustor, a total of six measurement positions were installed, each covering more or less the bed surface area associated to one of the six discharge hoppers. Figure 3.2 shows the position of the measurement probes. This set-up gives the most detailed information possible on the agglomeration status of the fluidised bed. Depending on operational experience it may be decided that only one "average" output is needed for monitoring and control.

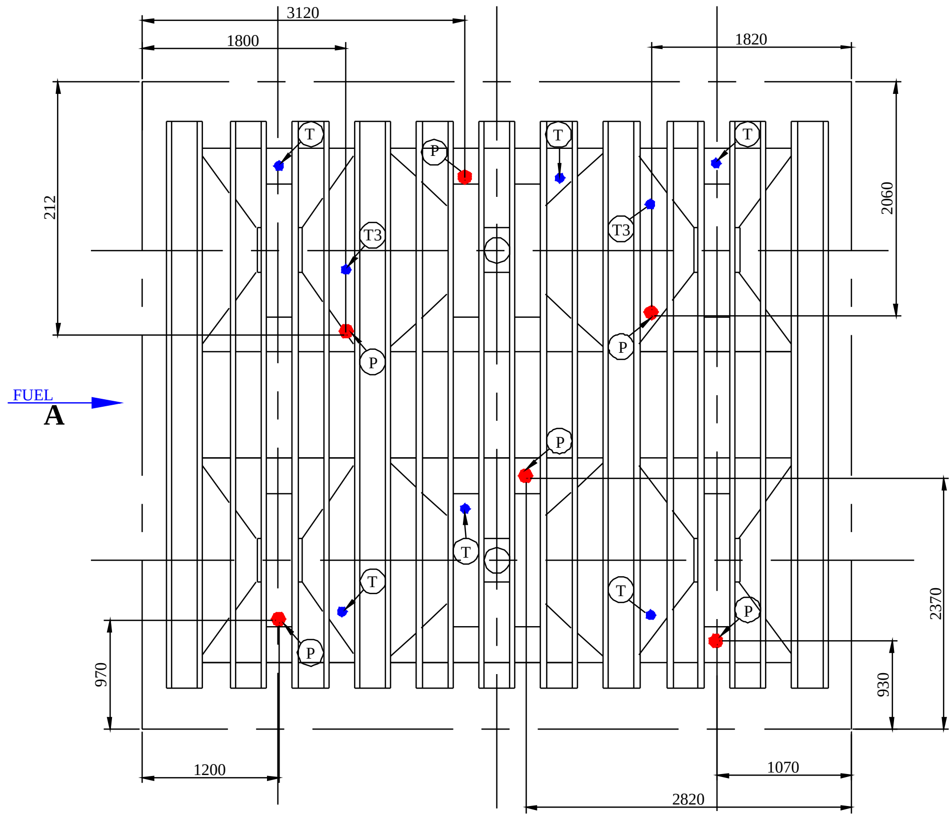


Figure 3.2 *Pressure fluctuation measurement probes in 80 MW_{th} fluidised-bed combustor: location of six probes (red circles).*

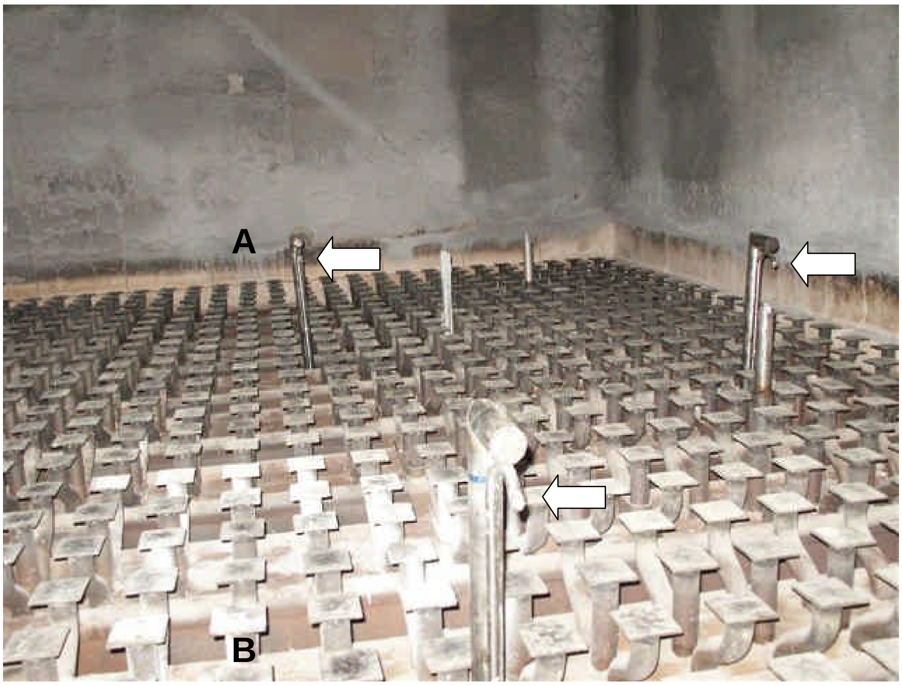


Figure 3.3 *Photo showing three out of six pressure fluctuation measurement probes (section A-B from Figure 3.2).*

Piezoelectric pressure transducers of Kistler type 7261 connected to the probes were used to measure the pressure fluctuations. The charge from the piezo element is amplified and converted to a DC voltage signal using a Kistler amplifier type 5011. Due to a time constant that can be set in the amplifier, the lowest frequencies are high-pass filtered with a cut-off frequency < 0.2 Hz. By this filtering action, the fluctuations of the pressure are measured relative to the local average pressure, *i.e.*, the off-set of the signal is zero. The signal from the pressure sensors was recorded by a high-end data acquisition system from LMS-DIFA type DSA300. The signals were simultaneously sampled and low-pass filtered with a cut-off frequency of one half of the sample frequency, satisfying the Nyquist criterion. Subsequently, 16-bit analogue to digital conversion was applied at a sample frequency of 80 Hz.

The Technical University of Delft developed a specially designed data acquisition and attractor comparison software. The data acquisition software 'RRDyMon' stored the data in automatically chopped data files. This resulted in a 80 MB data file each day, containing the pressure fluctuation data of the six channels. The attractor comparison software 'AttCom' was used to calculate the *S*-values for both static and moving reference settings (see Figure 3.4). There are both an online and an offline version of AttCom available: the online version directly calculates the *S*-values from the data obtained via RRDyMon. The offline version can be used afterwards to analyse the data with different calculation settings. To check if the pressure probes provided the correct signals, indicating that the probes functioned properly, a dedicated data visualization and analysis program 'RRInspect' was developed.

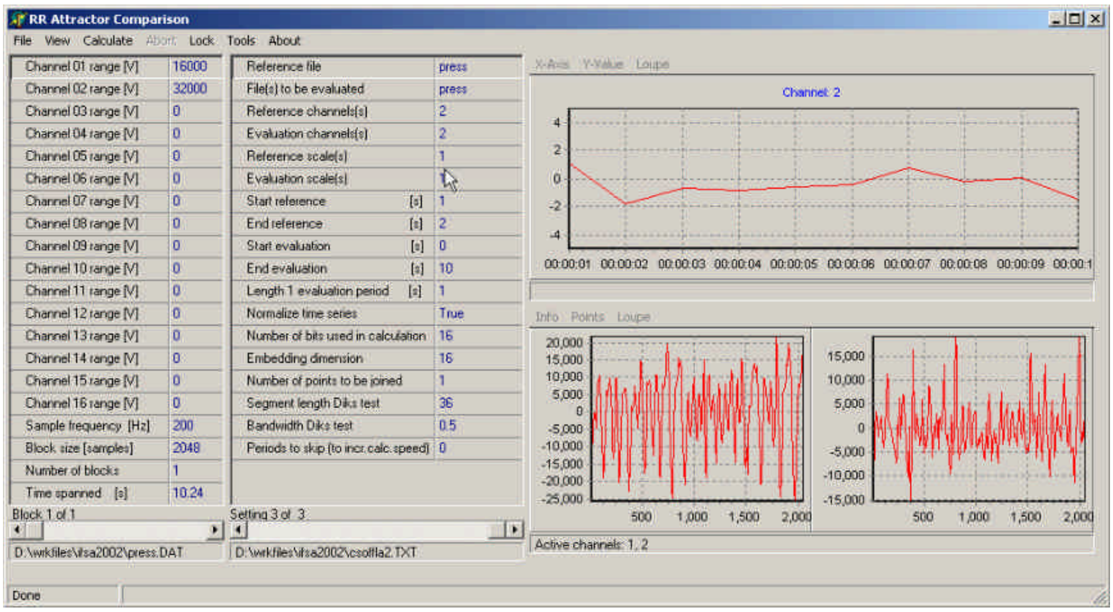


Figure 3.4 *A screenshot of AttCom. On the left-hand side, the settings are given. The upper right panel gives the S-value as a function of time; the measured pressure signals are given in the right bottom corner.*

3.1.2 Operation of the system

Several problems have occurred with the detectors:

- Some pressure probes, at some stage, they were accepted as 'non-functional'. In certain periods, this left only 2 to 4 pressure probes which supplied useful data (at least until the next stop).
- During operation the pressure probes sometimes were plugged with sand, resulting in unusable measurements until the next planned stop). Well-controlled purging solved this problem.

The EARS DAQ computer stored the data and showed online *S*-values for the 6 channels. The system frequently warned for agglomeration (*S*-values above 3) in the beginning of the project, while according to the operators no agglomeration was encountered. At that stage the EARS information was therefore not a serious trigger for process operators to react on. These first tests helped to develop the later implemented EARS techniques as filtering and moving reference. With this improved EARS prototype the false alarms were minimized. The absence of online communication between the research team and the EARS system installed in Cuijk, delayed the development and therefore also learning circle and involvement of the operators with the EARS system.

3.1.3 Suggestions for improvements

During operation, the pressure probes were damaged. Therefore a protective casing was installed around the detectors and the purge flow was increased. The initial casing as displayed in Figure 3.1 though, may have an effect on fluidisation behaviour of the bed, and does not provide optimal protection. The mechanical strength of the probes and welding could be improved. The initial absence of pressure reducers in front of the purge flow controllers possibly has affected the quality of the system by generating possible false alarms.

The research team should be able to react on the signals of the process computer from distance. Doing so, good communication between the administrator and the user of the system is crucial. This creates an environment in which fast response and accurate analyses of the situation can be made, the correct actions can be taken and the situation can be adjusted to one in which new useful results can be obtained.

3.2 Measurements and signal validation

After installation of the hardware, measurements were started to test the system and to establish know-how of the pressure fluctuation measurements in response to the fluidised bed combustion process and its normal variations. Based on this know-how, it becomes possible to distinguish between warnings from the EARS *S*-value that correspond to normal process variations and those, which may be caused by bed agglomeration.
Pressure fluctuation data were stored over long periods of time and for selected periods. In addition, the following process data were extracted from the station's logging system (5 minute interval): fuel flow, primary, secondary and tertiary air, fresh sand flow (bunker level), sand discharge (calculated), bed level (calculated from), bed pressure drop, bed temperatures, fresh water and steam flow, soot blower activation.
During these selected periods bed material was sampled and characterized, in order to obtain comprehensive information about the quality of the fluidised bed in relation to the output of EARS.

3.2.1 Sampling and analysis of bed material

During selected periods samples were collected from the fluidised bed. The samples were photographed and then sieved to obtain their size distribution. Here, the particle size distribution is considered a relevant measure for the state of agglomeration in the bed because particles with low-viscous coatings stick together and form small agglomerates which can be identified from a sieve analysis as a coarse fraction. Selected samples have been chemically analysed.

3.2.1.1 Process description

During the first six months of the project an industrial sieving installation was installed at the BEC power station to control the size of the particles in the fluidised bed within a narrow window. It was expected that sieving would reduce the concentration of initial agglomerates and other off-spec particles. This would optimise the quality of fluidisation and reduce the accumulation of larger agglomerates which could eventually disturb the fluidisation process. To minimise this risk, obviously, the rate of discharge of growing agglomerates is a key parameter. The effect of the sieve was evaluated by comparison of results from the measurement campaign before and after sieve installation.

The major solid flows in and out of the process are shown in Figure 3.5, without and with sieve respectively. Without the sieve, bed material was discharged and replenished "manually", based on visual inspection of the bed material, notably the concentration of 2-3 mm agglomerates. With the sieve the particle size of the bed material is controlled close to the specs of the fresh sand (a composite of 0.8-1.0 and 1.0-1.2 mm sand); with each discharge cycle particles larger than 1.2 mm are removed while the material passing the sieve is recycled to the bed. The sieve can be by-passed on demand.

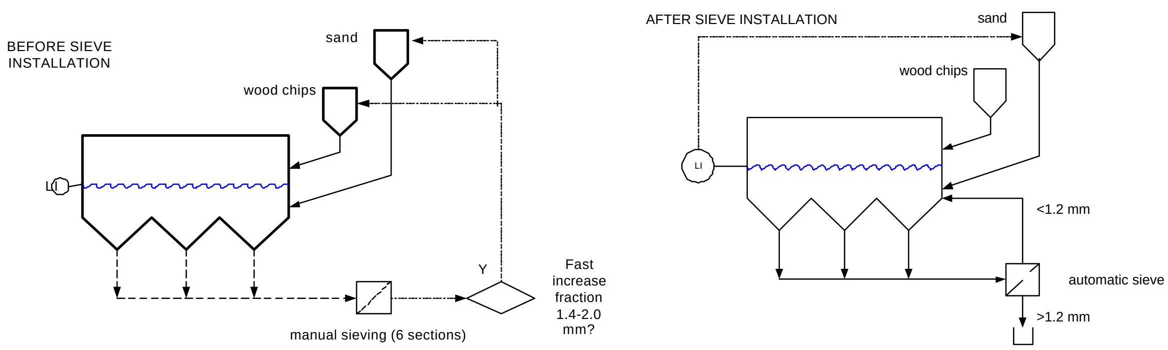


Figure 3.5 *Fuel, fresh sand and bottom ash flows before (left) and after (right) installation of sieve at BEC power station.*

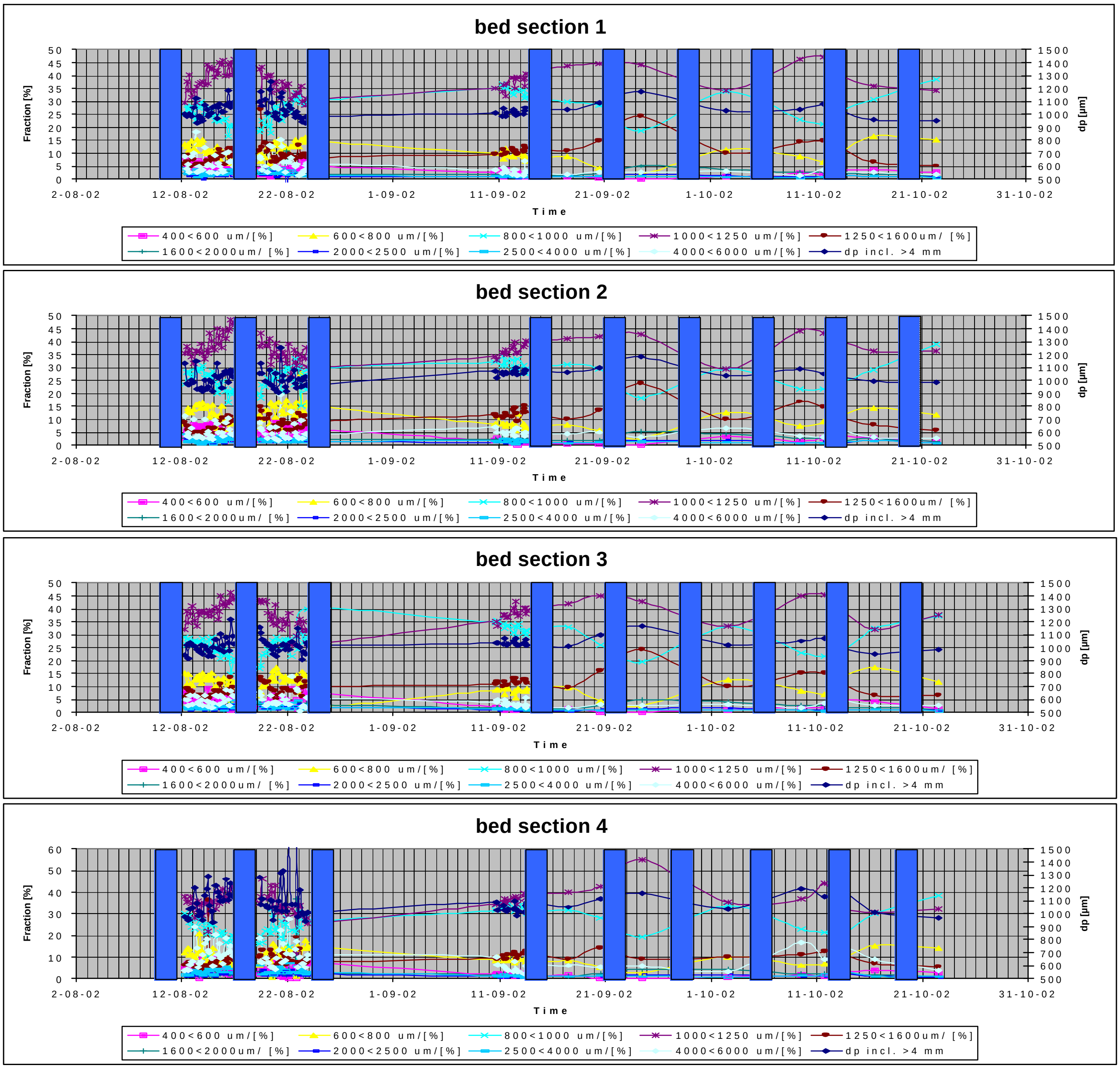
3.2.1.2 Methodology

The fluidised bed consists of six sections which can be separately aerated and discharged. During a discharge cycle each section consecutively discharges approximately 120 litre or 190 kg of bed material onto a belt conveyor. A 10 litre sample was collected from each discharge to evaluate the quality of the bed material per bed section. A photograph was taken and 1 litre of the sample was sieved. Selected samples were chemically analysed to evaluate the formation of ash coatings on the sand particles. Also various particle and fluidising properties have been determined using a laboratory scale fluidised bed facility.

3.2.1.3 Results

3.2.1.3.1 Sieve analyses

The results from the sieve analyses that have been performed over a 10 week period from August 12, 2002 to October 22, 2002 are shown in Figure 3.6.



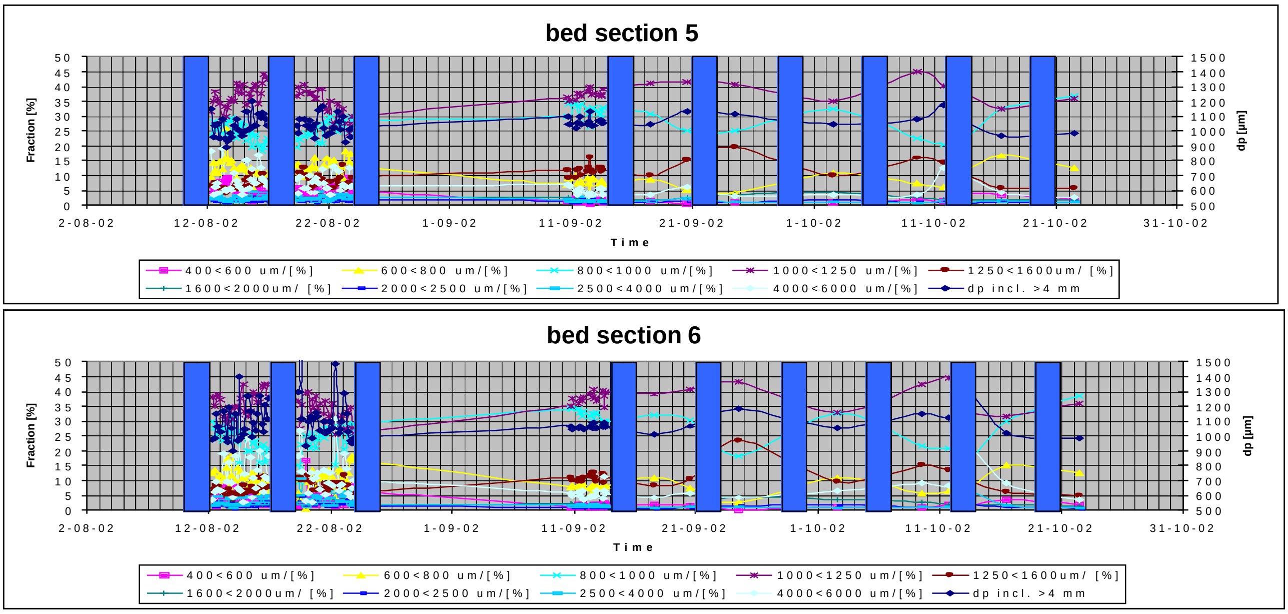


Figure 3.6 *Measured particle size distribution of the six bed sections over a 10 week period in 2002. Lines are only meant to guide the eye.*

Notes with Figure 3.6:

Week 35 (26.08.2002)	:	Installation industrial sieve (cut off 1.4 mm)
Week 41 (11.10.2002)	:	Change sieve cut off to 1.2 mm
Week 39 (25.09.2002)	:	Severe bed agglomeration occurred.
Note 1	:	Size fraction 400-600 µm contains also fly ash

From these results the following observations were made:

- The particle mean size of the spent sand is higher than for the fresh sand: 1000 vs. 960 µm.
- The fractions 800-1000 µm and 1000-1250 µm dominate the particle size distribution (together good for 60-70%), as would be expected from the fresh sand (800-1200 µm). The second-higher fractions are both below and above the fresh sand, namely 600-800 µm and 1250-1600 µm.
- All bed sections exhibit similar trends which corresponds with sufficient inter-section mixing of the bed material. Sections 4, 5 and 6 do have somewhat higher concentrations of 4000-6000 µm particles than sections 1, 2 and 3, which is most likely explained by the fact that the fuel (which contains sand, clay and small rocks) is fed over the bed at the side of sections 4, 5 and 6.
- The fractions 800-1000 µm and 1000-1250 µm exhibit a large variation; the bandwidth amounts approximately 15% (absolute) on a basis of 20-45%. Over the 10 week period, the bandwidth of the observed variations remains more or less the same and seems un-influenced by the installation of the sieve. The variations have an approximate period of two weeks, which remains up till now unexplained.
- The size fraction 1250-1600 µm, which is either a product of agglomeration or fuel contamination, correlates with the size fraction 800-1000 µm. Seemingly, both the fractions 1000-1250 µm and 1250-1600 µm increase at the expense of the 800-1000 µm fraction. This indicates that agglomerates may be formed from 800-1000 µm material, which thereby grows into the >1000 µm fractions. This mechanism suggests that the 1250-1600 µm fraction is a good indicator for agglomeration, which was confirmed by the peaking of this fraction on September 24th, one day before severe agglomeration occurred.
- During the first seven weeks of sieve operation, the mean particle size did not significantly change in comparison to the pre-sieve period.

- In most sections, the installation of the sieve seems to have reduced the fraction of 4000-6000 µm particles. The fraction 1000-1250 µm on the other hand, mostly increased. Although the number of measurements are few, it seems that the installation of a finer sieve (1.2 mm) on 11-10-2002 has resulted in a decrease of the indicative 1250-1600 µm fraction.

3.2.1.3.2 Chemical analyses

To evaluate the composition and amount (thickness) of the ash coating on the sand particles, samples collected on 12.08.2002, 16.08.2002, 13.09.2002 and 24.09.2002 have been chemically analysed for the elements Si, Al, Fe, Ca, Mg, K, Na, P, S. The first two samples were collected before the sieve was installed, while the remaining two were collected when the sieve was in operation. Of each sample the size fractions 500-710, 710-1000 and 1000-1180 µm were separately analysed to see particle size dependencies. Figure 3.7 gives the measured element concentrations of the different samples and size fractions. The concentrations of the elements Si, Al, Fe and S are not shown, but were around 350 g/kg, 8 g/kg, 5 g/kg and 80 mg/kg, respectively.

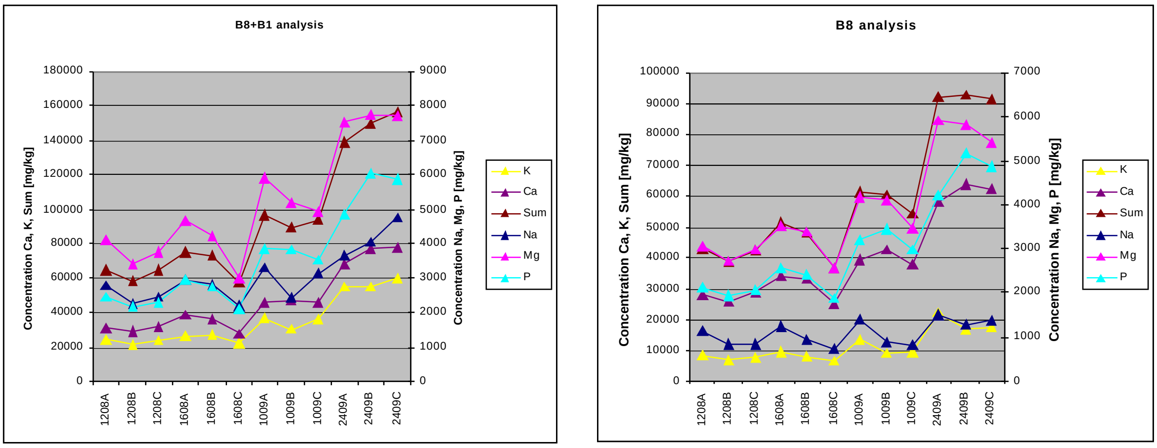


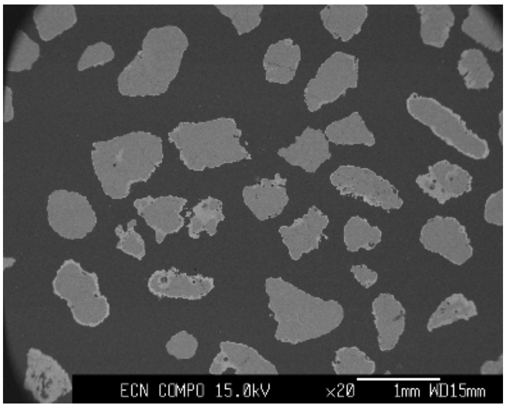
Figure 3.7 *Chemical composition of bed material samples collected before (1208 and 1608) and after (1309 and 2409) installation of the sieve. A, B and C refer to size fractions 500-710, 710-1000 and 1000-1180 µm respectively. The left figure gives the whole particle composition, while the right figure gives the composition of predominantly the outer particle layer (first, partial digestion).*

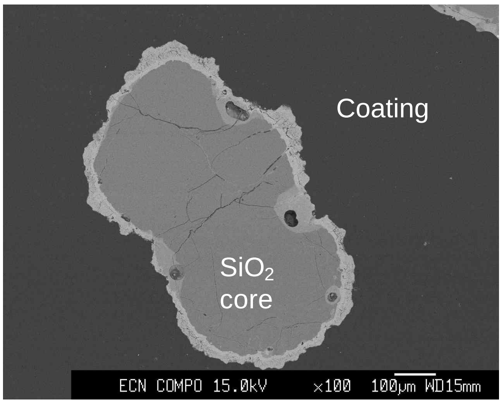
The following observations were made:

- The concentrations of the elements Ca, K, Mg, P, Na and certain trace elements have all considerably increased when the sieve was installed; their summed concentration increased by a factor of 2.5 from 60 g/kg to 150 g/kg. This increase was counterbalanced by a decreased Si concentration. The concentrations of the elements Al, Fe and S were constant and not influenced by the sieve.
- 75-90% of the elements Ca, Mg and P is released in the first (partial) digestion step of the analysis procedure, which means that these elements are predominantly present in the outer layer (=coating) of the bed particles. The elements K and Na are released for 30-40% in the first digestion step, meaning that these elements are significantly associated with the silicon particle core which is only completely released after the second digestion step.
- A particle size dependency of the element concentrations can be seen but is not well-developed in each case. The particle size dependency observed cannot be explained by an equal coating thickness but, in stead, suggests an increasing coating thickness with particle size. From a mechanistic point of view it seems unlikely that larger particles will accumulate a thicker coating than smaller ones. Therefore it is argued that the observation may be explained by initial agglomerates which have accumulated relatively large amounts of ash. Further indications supporting this are given below.

- The ratio of the elements Ca, K, Mg and P was not changed by the installation of the sieve; therefore, the recycling of bed material does not change the composition of the coating on the sand particles.

Cross-sectional SEM-EDX analysis of bed material samples showed a distinct influence of the sieve on the particle structure and coatings. Figure 3.8 shows two images taken from the 12.08.2002 sample, Figure 3.9 for the 24.09.2002 sample.





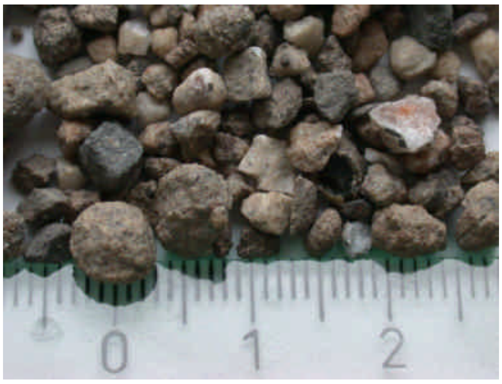


Figure 3.8 *SEM backscatter (top) and optical images (bottom) of 12.08.2002 bed material, collected before installation of the automated sieve. Most particles consist of a single (not-fragmented) SiO_2 core with an ash coating on the outside.*

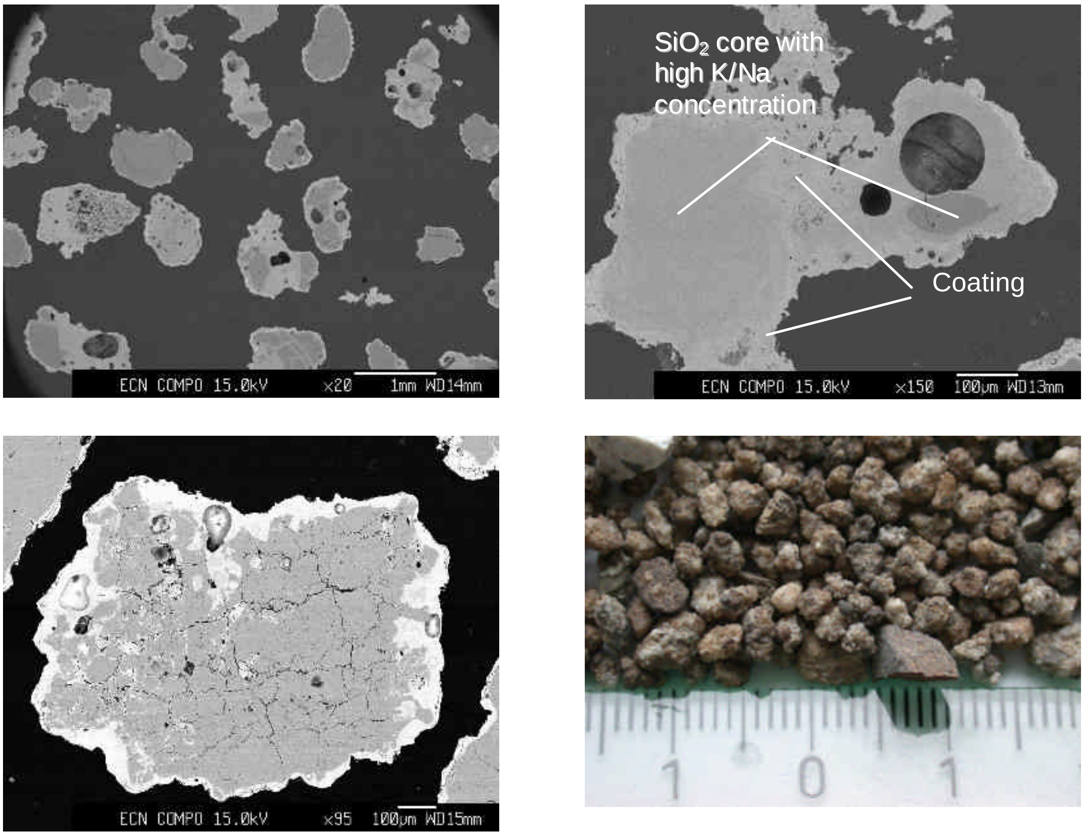
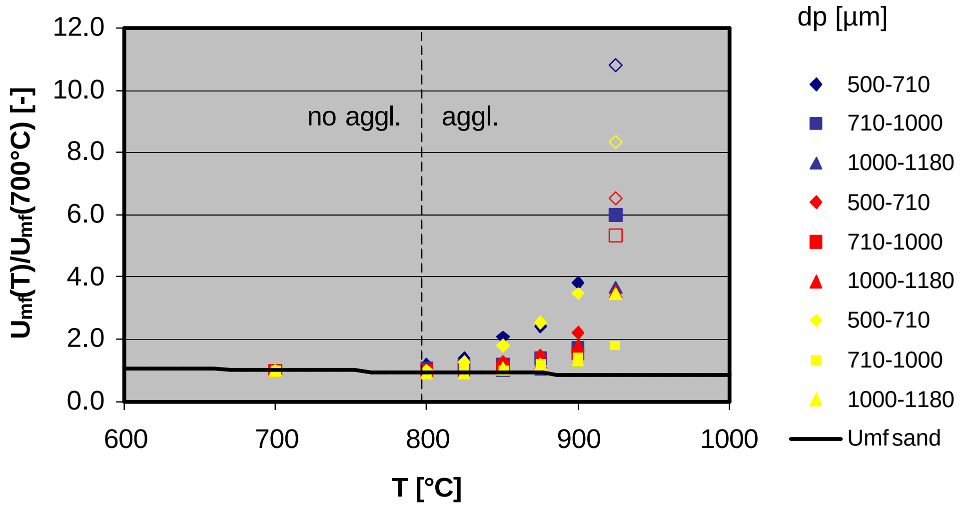


Figure 3.9 *SEM backscatter and optical images (bottom right) of 24.09.2002 bed material collected after installation of the automated sieve. Many particles consist of multiple SiO_2 core fragments with an ash coating between them and on the outside. The originally (pure) SiO_2 core particles are often 'impregnated' with significant amounts of K and Na. The bottom-left image shows many cracks inside the SiO_2 core particle.*

With the sieve, particles smaller than 1.2 mm are recycled and re-used, effectively prolonging their lifetime. Due to the repeated cooling and heating in the cycle of discharging, sieving and recycling, the particles undergo thermal stress which leads to crackling and fragmentation. The partly coated fragments are coated repeatedly as a consequence of their multiple passes through the combustor, until they become large enough to be separated by the sieve. In conclusion, a large proportion of the bed consists of multi-fragment agglomerates which have a size which approximately equals the size of the original fresh sand particles. The tiny agglomerates have a relatively large ash mass fraction of about 30%.

3.2.1.3.3 Stickiness and fluidising properties

With a number of samples, high-temperature fluidisation tests were carried out to demonstrate the temperature-dependent stickiness of the ash coatings observed in the bed material. The tests were carried out in a 5 cm ID electrically heated fluidised bed facility in the temperature range 25-1000 °C. The results have been plotted in Figure 3.10 as the ratio of U_{mf} measured at temperature T and U_{mf} at 700 °C. Below 700 °C the measured values of U_{mf} were found equal to the theoretical value calculated for the fresh (uncoated) sand given in Figure 3.10.



blue symbols	: 12.08.2002 sample (without automated sieve)
red symbols	: 16.08.2002 sample (without automated sieve)
yellow symbols	: 13.09.2002 sample (1.4 mm automated sieve in operation)
open symbols	: a situation of irreversible defluidisation was encountered

Figure 3.10 *Minimum fluidising velocity measured for various bed materials as a function of temperature. The lines represent the calculated theoretical value.*

From these results the following observations were made:

- For all samples and up to 800 °C, the measured minimum fluidising velocity equals the calculated theoretical value.
- Above 800 °C the measured U_{mf} value increasingly deviates from the theoretical value due to viscosity changes in the ash coating, leading to increased stickiness.
- At a temperature of 940 °C a fluidising velocity of roughly five times U_{mf} is needed to prevent de-fluidisation as a result of sticky forces exceeding break-up forces.
- For some cases the effect of stickiness is influenced by particle size, but overall the results are inconclusive in this respect.
- There is no conclusive difference between the effect of stickiness on the minimum fluidising velocity of the bed material before and after installation of the sieve. This suggests that the viscosity of the ash coating – which is determined by the chemical composition and the temperature and which is quite similar for both bed materials – dominates the stickiness.

3.2.1.3.4 Particle morphology

It was pointed out in section 2.2.2 that the *S*-value is influenced by changes in particle size distribution, shape (sphericity), density and the high temperature effect of the viscosity of ash coatings on fluidising behaviour.

As can be seen from Table 2.3 in section 2.2.2, the density of the bed material is the same for all samples and not influenced by the building of an ash coating around the bed (sand) particles. The sphericity of the bed particles, however, does increase significantly compared to the fresh sand. It was found that this was not due to attrition (wear by friction) and the increase is therefore attributed to the smoothing effect of molten ash coatings.

When used bed material from the industrial installation is subjected to fluidised bed combustion again, the already cracked particles (see Figure 3.9) easily fall apart into small fragments with a sphericity resembling the original fresh (read sharp) sand. This phenomenon is likely to take place repeatedly during the cycle of discharge, external (cold) sieving and recycling of bed material.

3.2.2 Correlating EARS and bed quality

The ultimate test of the EARS sensitivity would be monitoring the agglomeration process until complete defluidisation of the industrial combustor. Notwithstanding the relevance from a research point of view, this would result in complete plant shutdown with all the financial consequences, and such a test is not feasible. The second best test would be to correlate *S*-values to the analyses of the bed particle samples.

During a test period in week 33.2002 one of the six pressure probes was monitored (other probes were not available) for the relation between the *S*-values and the changes in particle size, measured by sieve analyses of the recycle stream (see Figure 3.11). During this test the sieve installation was by-passed. After plant shutdown the pressure probes were inspected and it was determined that the other five pressure probes were damaged or blocked due to the absence of a purge flow. The pressure probes used in this trial were upgraded to an improved design.

Figure 3.11 shows a positive correlation between the *S*-value and the mass fraction of bed particles of the size 1.0-1.25 mm, which are considered from operator experience as an important indicator for the agglomeration 'status' of the bed.

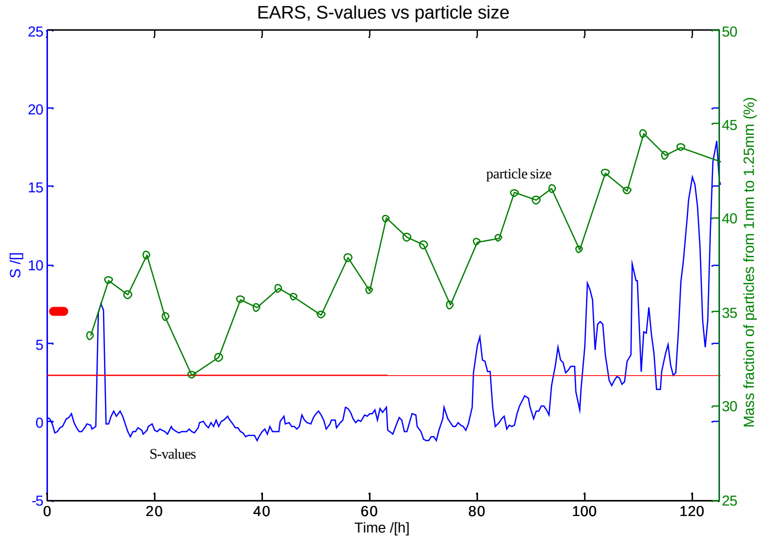


Figure 3.11 *The relation between the S-value measured at pressure probe position no.2 and the changes in particle size, measured by sieve analyses of the recycle stream in week 33.2002. The reference time period is symbolized by* • .

Although the stickiness of bed particles was not determined for all samples, it may be argued that a change in stickiness could have resulted in a similar effect on the *S*-value as observed in Figure above. In section 3.2.1.3.3, Figure 3.10 demonstrates the variation of stickiness (in terms of U_{mf}) between various samples and, subsequently, Figure 2.10 in section 2.2.2 demonstrates how this may influence the measured *S*-value. Still, the role of such an effect in the measurements given by Figure 3.11 is not conclusive.

3.3 Method optimisation

3.3.1 Filtering process variations

EARS is used to detect the sporadic event of agglomeration, and therefore should not detect *e.g.* small variations in superficial gas velocity, bed mass, pressure drop or bed temperature. The cold flow experiments already illustrate that EARS will not be influenced by changes in bed mass and superficial velocity if the variation stays within approximately 10%. During a test period of the industrial prototype of EARS at the Essent 80 MW_{th} wood-fired BFB combustor, fluidisation conditions were fluctuating due to normal process operation. During this test period the operators and EARS observed no agglomeration. In this period 28 relevant process variables were recorded and analysed, one of which is the superficial gas velocity or fluidisation velocity.

Figure 3.12 shows the *S*-values versus the normalized deviation of the fluidisation velocities. In this period the variations in superficial gas velocity stayed within 10%. As mentioned, no agglomeration was detected, resulting in *S*-values under the alarm limit of 3.

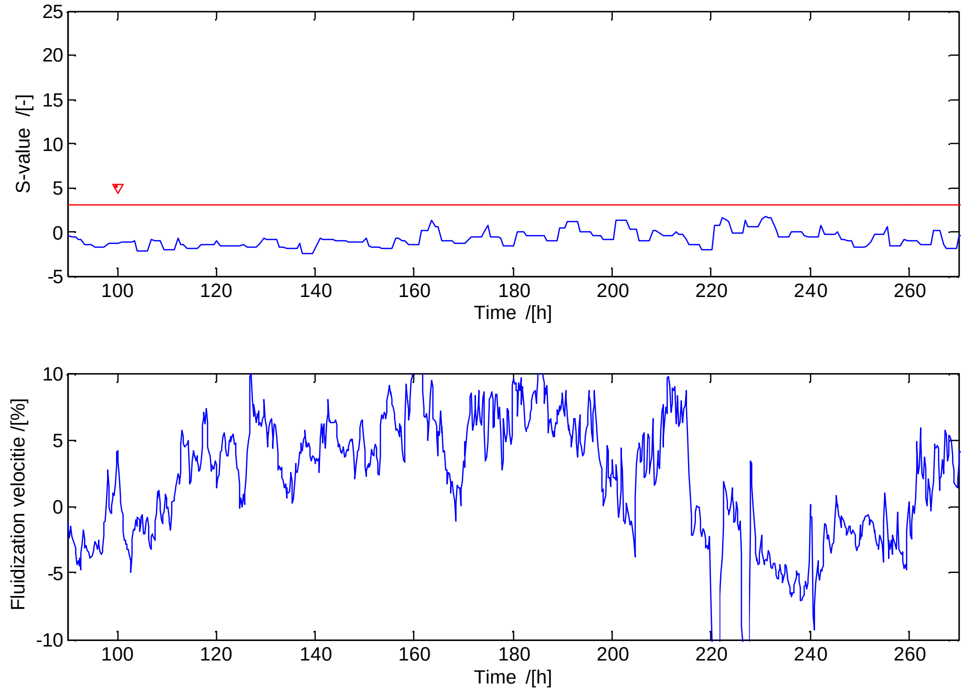


Figure 3.12 *Monitored S-values values versus the normalized deviation of the fluidisation velocities. The reference time period is indicated by* • .

Since the bed height was not recorded, the pressure drop over the bed was evaluated, which is an indirect measurement of the bed height. Figure 3.13 shows the normalized deviation of the pressure drop over the fluidised bed.

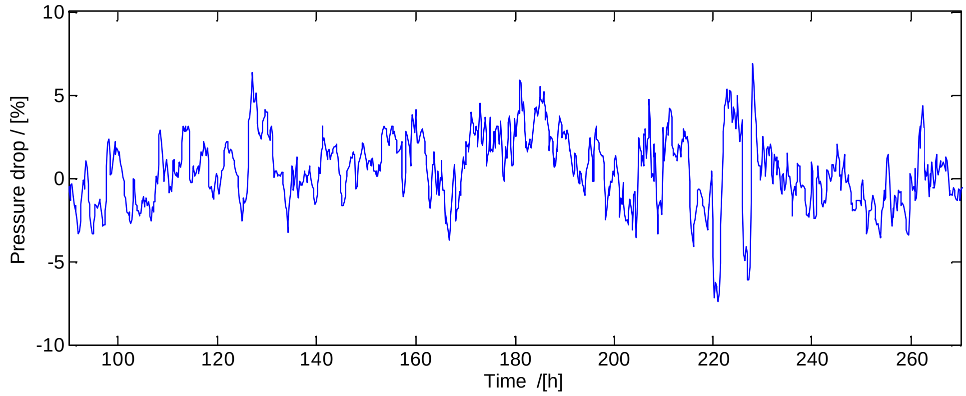


Figure 3.13 *The normalized deviation of the pressure drop over the fluidised bed.*

All tests and analyses of the process data of the fluidised bed combustion plant confirmed the cold flow experiments, EARS being insensitive to small variations in process conditions as superficial gas velocity, bed mass, pressure drop or bed temperature.

During normal process operation, operators sometimes have to change or vary process conditions, *e.g.* they have to decrease the production because of lower demand. In other words, during normal operation large variations in process conditions may occur. When these large variations are encountered, one option is to use a reference time series for every 'typical set' of operating conditions. This method works provided that these typical sets of operating conditions will occur during normal process operation and are long enough to soften normal process fluctuations caused by these changes in process conditions. A dynamic or moving reference time-series is therefore a more applicable method for process variation with a large time-scale due to the operation of an industrial combustor. This method is newly developed and is able to cope with these large process variations. It will be described in the next section.

3.3.2 Static and moving references

Normally, the attractor comparison method compares a static reference time period with the online measured pressure fluctuations. The attractor comparison software [6] calculates the *S*-value by comparing pressure fluctuations within a 'fixed' time window, with the pressure fluctuations time window that has to be evaluated. The monitoring feature is obtained by shifting the evaluating window in time and is called the 'static reference' or 'fixed reference' method (see Figure 3.14).

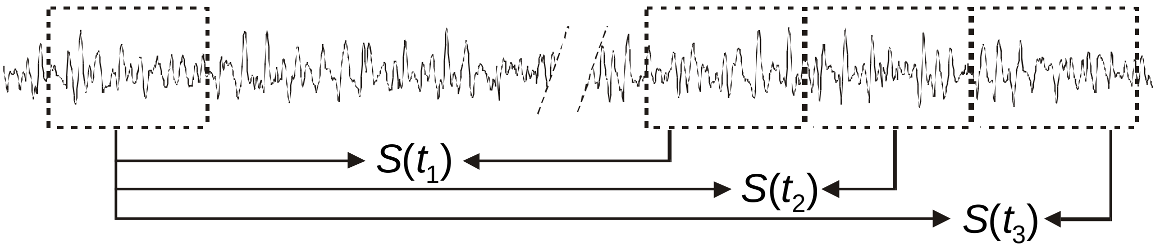


Figure 3.14 *Example of the static reference method. The monitoring feature is obtained by comparing the attractors of a static reference period with attractors from evaluated pressure time windows at t_1, t_2, t_3 to the last obtained pressure time window.*

The static reference method is insensitive for small changes in process conditions. When larger variations with a relatively long time-scale are encountered a dynamic or moving reference time-series is a more applicable method. This method maintains a constant time delay between the reference time window and the evaluated time window. Figure 3.15 illustrates the 'moving reference' method, showing the calculation of the *S*-value at time window t_1 using reference period A and evaluation period A. Subsequently, the monitoring progresses by evaluating periods B to obtain $S(t_2)$, periods C to obtain $S(t_3)$, and so on.

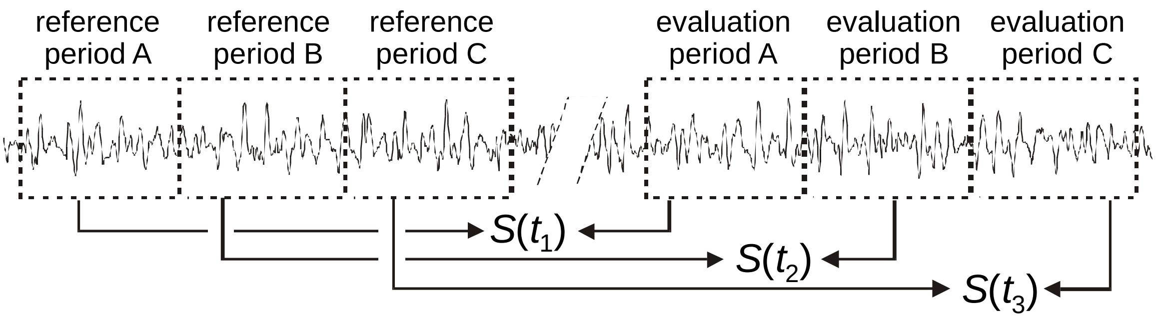


Figure 3.15 *Example of the moving reference method. The S-value is obtained by comparing the attractors of a moving reference period with attractors from evaluation pressure time series. Both windows progress in time from A to B to C etc. The time delay between the reference and evaluation time window is constant.*

When a process disturbance occurs or the bed agglomerates, both an *S*-value calculated with a moving or a fixed reference will detect this (S>3). Due to the concept of the moving reference, the moving reference method will detect the disturbance twice. Figure 3.16 illustrates this phenomenon. The first alarm will occur at the same moment as with the static reference method. The second alarm from the moving reference will occur after the constant time delay between reference and evaluation period. Figure 3.17 gives an example of this phenomenon in practice.

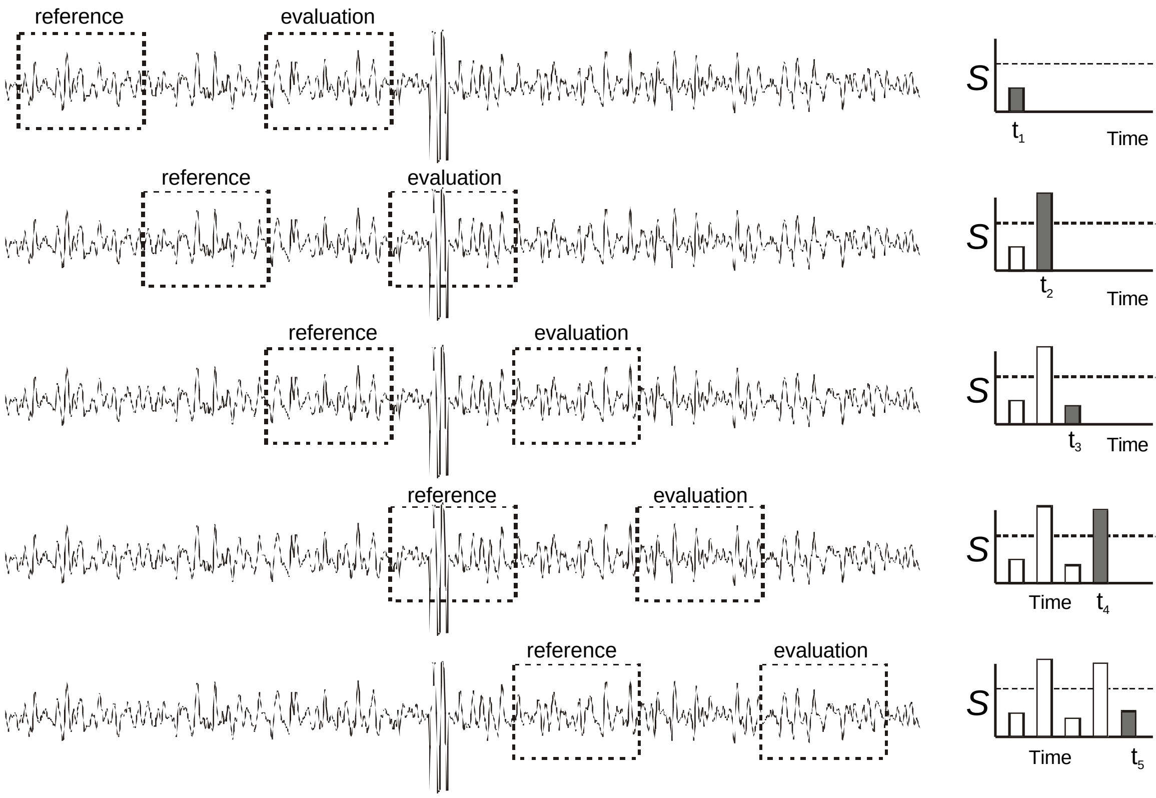


Figure 3.16 *Example of the moving reference characteristic signalling a disturbance twice. At t_1 no alarm is generated. At t_2 a disturbance in the process is recorded and therefore an alarm (S>3) is obtained. After the disturbance, at t_3 both reference and evaluation period representing normal operation and no alarm is given. At t_4 the reference period represents the time window in where the disturbance occurred which will result in a second, but false alarm. After a specific time, at t_5, both reference and evaluation period represent normal operation.*

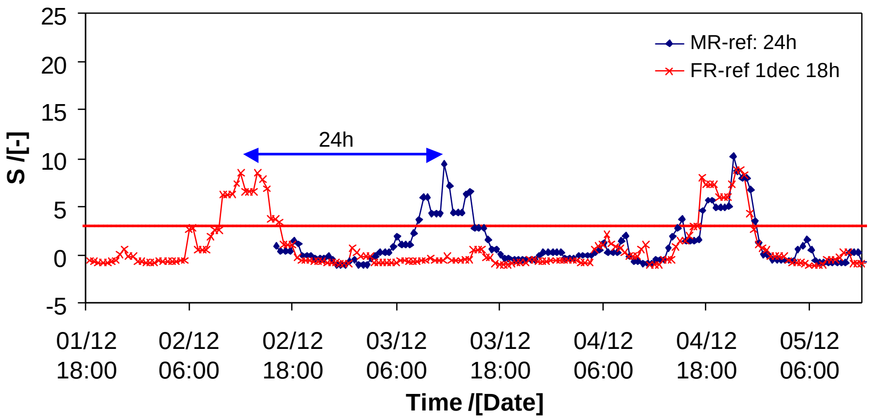


Figure 3.17 *Example of the moving reference characteristic signalling a disturbance twice during the test period in week 49.2003 in the Essent 80 MW_{th} BFB combustor.*

3.3.3 Filtering irrelevant warnings

Although the method is insensitive for small, quick variations in process conditions and larger, slow variations can be handled by the moving reference method, some process variations are still not recognized by the operators or not measured. These unknown process variations may cause EARS to raise a false alarm. To overcome this problem, EARS includes the possibility to ‘filter’ the original *S*-value, by taking the minimum *S*-value of *n* consecutive *S*-values. While the non-filtered *S*-value correspond with a 95% confidence level stating that the hydrodynamic behaviour of the fluidised bed has changed, a filtered *S*-value (with *n*=3) has a confidence level of more than 99%. The effect of filtering is illustrated for both lab-scale experiments in Figure 3.18 and for monitored time series in the industrial combustor in Figure 3.19.

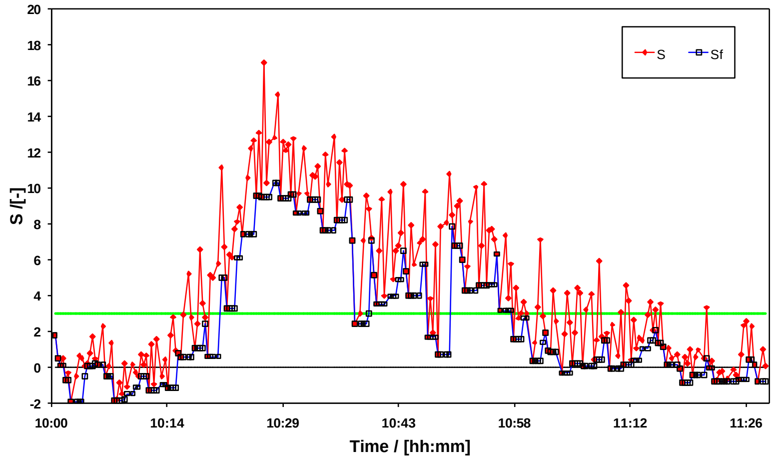


Figure 3.18 *The effect of filtering illustrated with a lab-scale experiment, where S is the non-filtered S values and S_f the filtered S-values.*

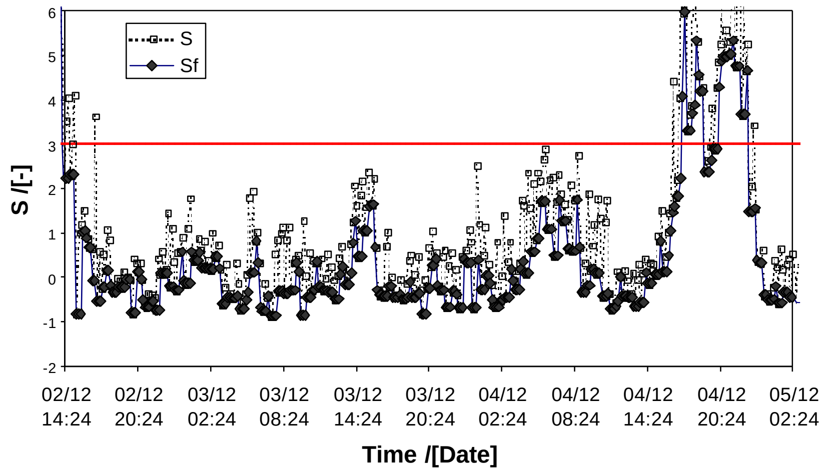


Figure 3.19 *The effect of filtering illustrated during a monitored time series in the Essent combustor (S_f represents filtered values).*

The time period defined as the reference period is crucial for detecting agglomeration. Figures 3.20A and 3.20B show the filtered *S*-values and the location of the reference time periods during monitoring test period in week 13 to 15 (2003).

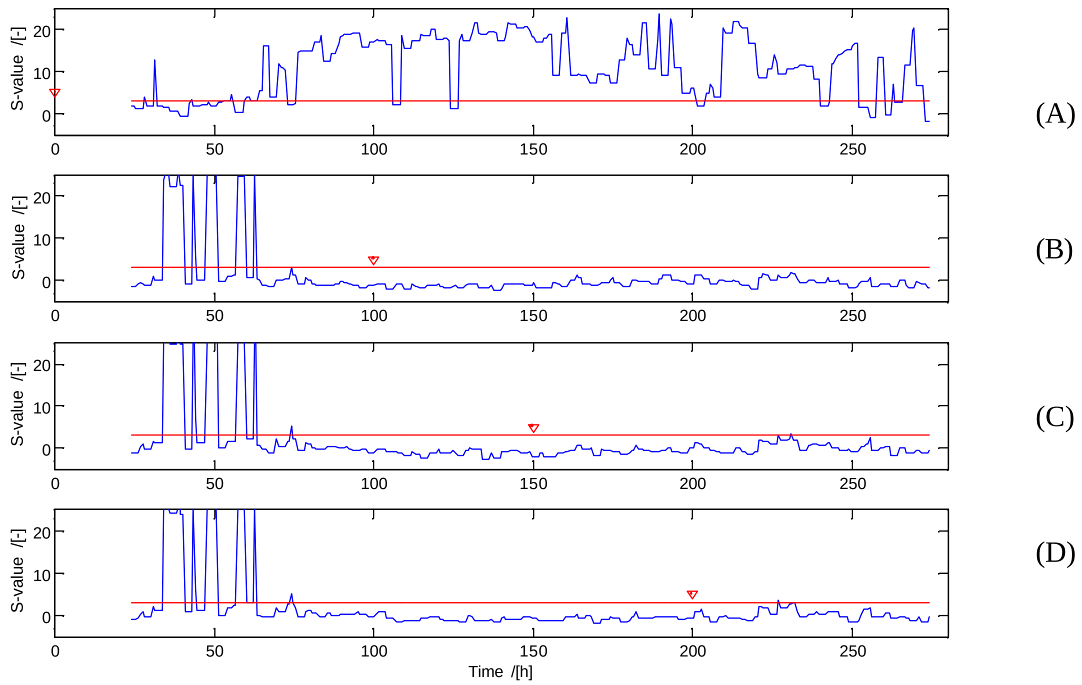


Figure 3.20 *Results will be influenced by the location of the reference time period, indicated by* • *. Situations A to D represent the effect of the location of the reference period on the filtered S-values during a test period in week 49. (A): the reference period is located in a different process operation regime. (B) to (D): the reference period is taken at various moments in the same and constant operation regime.*

From the point of view of process operations it was known that 'alarms' raised between 25h and 65h were false. Figure 3.20A shows the result of monitoring the actual process operation with a reference period that belongs to a different process operation regime. Figures 3.20B to 3.20D indicate that after 65h the process was stabilized and up to 300h no agglomeration was detected.

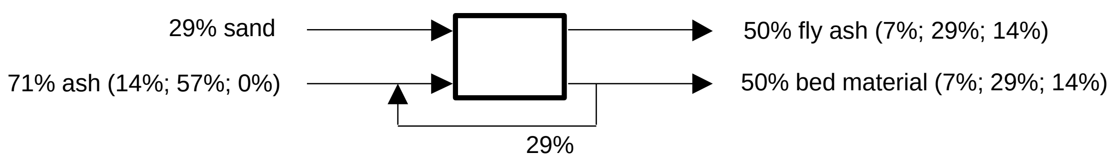
3.4 Agglomeration control

3.4.1 Control options

To control agglomeration various options are available and applied in practice, such as sand replacement, reduction of thermal load or change (increase) of fluidisation velocity. The options differ in effectiveness and can be classified accordingly as:

a) Structural control. Selection of fuel or fuel blends, bed material and process operation are control options to suppress agglomeration in a structural way with lasting, long-term effects, if done properly.
b) Symptomatic control. When the fluidisation behaviour of the bed is disturbed by the formation of larger agglomerates, this symptom can be detected by in-bed temperature or pressure drop measurements. Options to prevent escalation of such a situation have the purpose to minimise direct operational risks and to create a time window for actions which will have a longer lasting effect. Examples of symptomatic control are the temporary reduction of thermal load (fuel feed rate) or fluidisation velocity or additional air injection, to allow time for bed material replacement to take effect. Once stable operation has been re-established, the temporary measures can be lifted.
c) Pre-symptomatic control. EARS offers preventive control of the quality of the bed material such that the phase of aforementioned symptoms is not reached. Early detection and appropriate actions such as controlled bed material replacement are a prerequisite.

For the test with the Essent 80 MW_{th} BFB combustor, the combination of the agglomeration detection system with replacement of bed material was considered the most promising option. A reduction of operating costs associated with sand consumption and disposal of bed material was another incentive. The process was analysed to establish the window available for controlling and reducing the replacement of bed material.
In the 80 MW_{th} installation the addition of fresh sand is fixed by a control cycle in which all bed sections are consecutively partially discharged. The discharged material is sieved and a size fraction close to the sand specs is returned to the bed. From various operating data, a rough mass balance was established, see Figure 3.21.



note: (x;y;z) refers to (fuel-ash in biomass; fuel-attached sand/clay; added sand)

Figure 3.21 *Overall mass balance inorganic matter in Essent 80 MW_{th} BFB combustor.*

Theoretically, the fluidised bed could be maintained by ash introduced with the fuel, without feeding additional sand into the bed. However, from the point of view of bed quality, it may not be desirable not to have some control of the type of material entering the bed. Therefore a minimum make-up of fresh, well-specified sand is needed. The window available for variation of the feed rate of fresh sand is examined hereafter.

For a longer period of time, the mass flows of the BFB combustor were recorded. When the automated sieve was installed the feed rate of fresh sand was reduced to 29% of the total inorganic input (see Figure 3.21). This value represented the maximum level because the rate of sand replacement was limited by the capacity of the belt conveyor system removing the discharged bed material, minus the amount of bed material recycled from the automated sieve. The bed material discharge cycle has a fixed duration, after which a hopper is activated and a fixed amount of fresh sand is sent to the bed, unless the bed height exceeds a preset value.

The recorded mass flow data also showed a fairly strong correlation between the fly ash mass rate and the amount of ash introduced with the fuel. Sand and clay particles attached to the fuel make up about 79% of the input inorganic matter and are, to a large extent, elutriated from the bed to produce fly ash. Examining the mass balance, it was found that a part of the fresh sand added to the system also produced fly ash, most likely through the mechanism of particle fragmentation as explained in section 3.2.1.3.2.

From these findings it was concluded that the current (constant) rate of sand make-up was perhaps not entirely needed to maintain a desired bed quality and thus, perhaps, could be further optimised (reduced). For the EARS prototype test, therefore, a new control window between 16% and 29% of the total inorganic input, corresponding to discharge cycle times between 4.5 and 2.6 hours was agreed.

3.4.2 Process control - prototype

To test the EARS prototype in the last phase of the project a process control was developed. It was agreed that an instruction set should be presented to be used by the Essent operating staff in the event that an agglomeration warning or alarm would be encountered. Any controlling actions to be taken would then be based on the EARS instruction set.

In addition to this, a visual interface should be developed between the EARS monitoring system and the operating staff, to provide clear information about the agglomeration status of the fluidised bed.

3.4.2.1 EARS software modifications

During the application of the attractor comparison software in the BFB combustor, it was found that the *S*-values were fluctuating too strongly for a proper interpretation by the process operator. Therefore, the filtering procedure as described in section 3.3.3 was included in the software. For the final test period in week 49 (2003) an extra visualization was embedded in the attractor comparison software. An example of the display available for the operating staff is given in Figure 3.22.

The user could set criteria to change the colour of the windows in which the *S*-values of the six bed sections were displayed, corresponding to their respective agglomeration status: yellow to signal a warning, and red to signal an alarm (see for the criteria Figure 3.23). Only the operator can reset the red colour. To prevent interruptions by unauthorized users, a lock option was included in the final software version.

3.4.2.2 Setting up a control strategy

The EARS instruction set was developed as an algorithm which schematically describes when and how to re-increase the discharge cycle time, using the above described software. The instruction set is given in Figure 3.23.

At first, the *S*-value will be below 3. When one of the filtered *S*-values exceeds 3 (*i.e.*, three subsequent *S*-values > 3), the *S*-value of the corresponding bed section will become yellow (warning status). If the warning can be explained by non-relevant causes (not having anything to do with agglomeration, such as *e.g.* a change in the primary air flow), the process operator can manually reset the system to a no-warning status. If the filtered *S*-value becomes lower than 3 again, and stays lower than 3 for 24 hours, the yellow colour will be reset automatically. On the other hand, if two filtered *S*-values are larger than 3 within a block of six values, the colour for that measurement position will change to red (alarm status). If three or more of the six measurement points (bed sections) become red, the operator has to decrease the discharge cycle time to 2.6 hours. If this does not result in a decrease of *S* within one hour, the automatic sieve will have to be by-passed to force replacement of bed material beyond the maximum capacity of the conveyor belt. When the filtered *S*-value is again lower than 3, the discharge cycle time can be increased again to 3.6 hours and the process operator should manually reset the system.

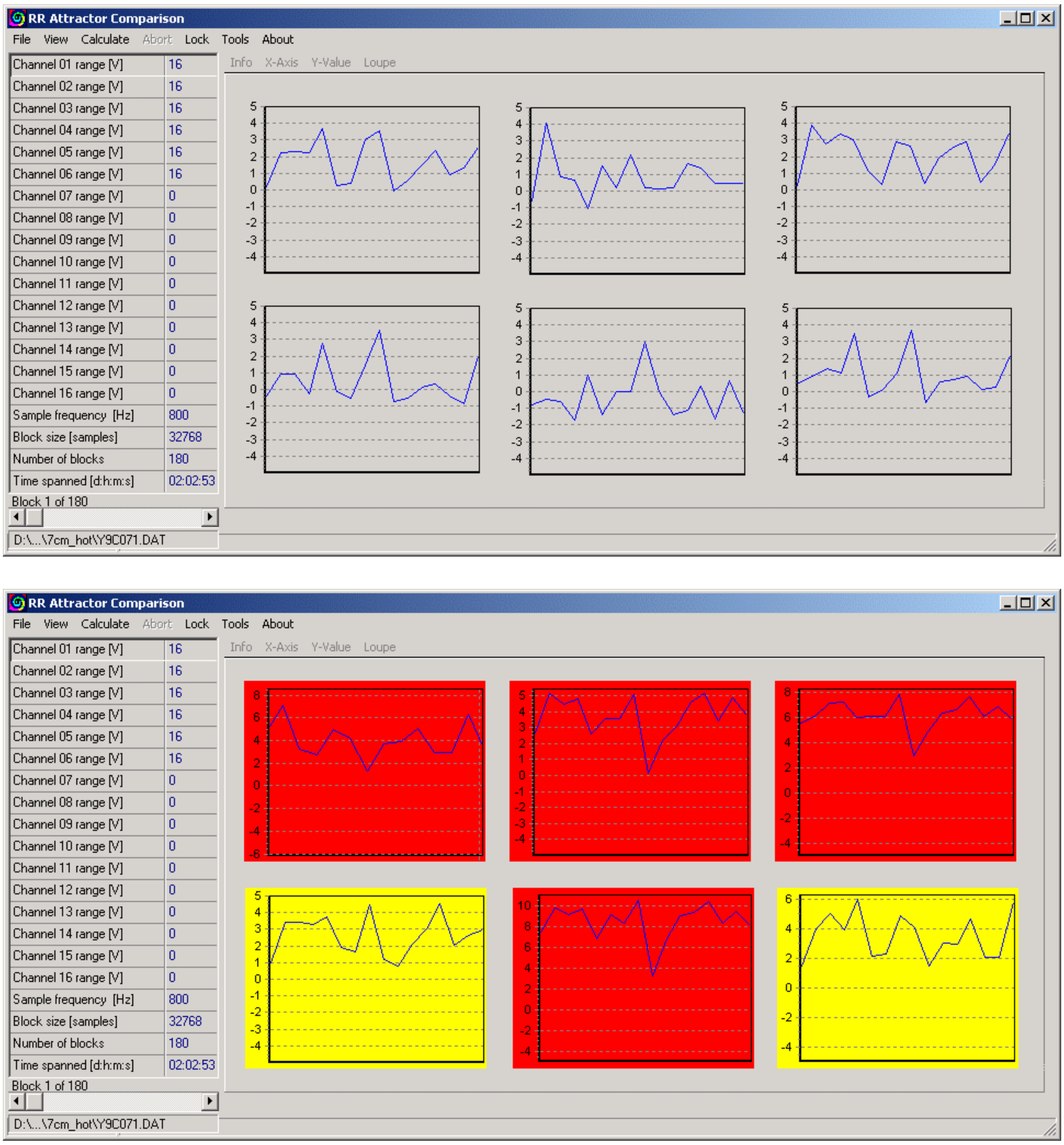


Figure 3.22 *Screendumps of the EARS prototype for testing by the BFB operating staff. Top: all six bed sections normal; bottom: two bed sections give an agglomeration warning, four give an agglomeration alarm.*

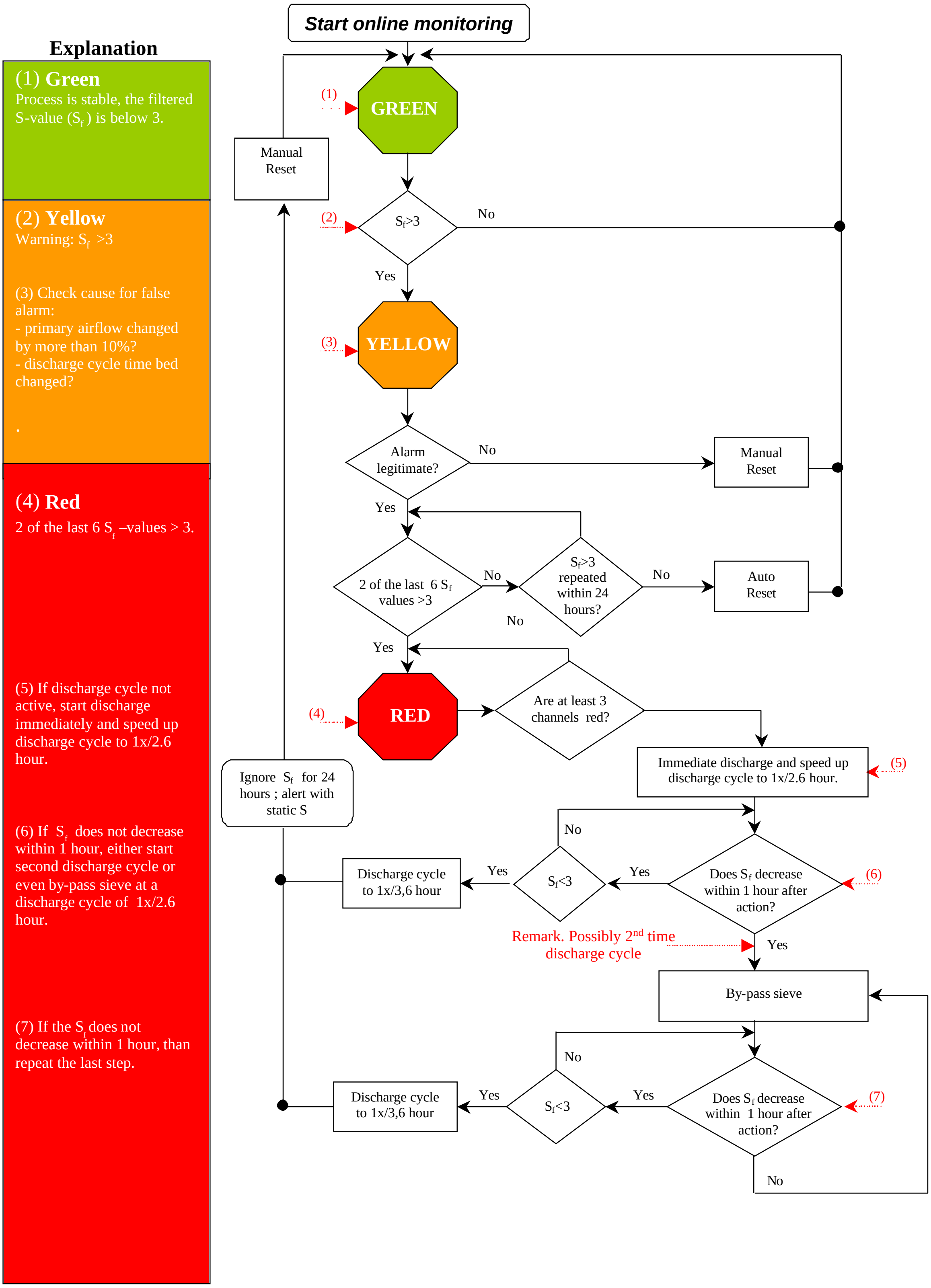


Figure 3.23 *Instruction set for EARS-based agglomeration management controling the rate of sand replacement in the Essent 80 MW_{th} BFB combustor.*

3.4.3 Prototype testing

3.4.3.1 Test programme

The prototype test was scheduled in week 49.2003, prior to a planned outage. Given the control window derived in section 3.4.1 for the make-up of fresh sand, it was decided to start the test week by extending the weekend control regime with a discharge cycle time of 3.6 hours, corresponding to about 21% of the total inorganic input. Halfway week 49 the cycle time would be further decreased to 4.5 hours, thus lowering the make-up rate to about 16%. This would deteriorate the bed quality during the course of the week and would allow for testing of the EARS prototype. In case of an agglomeration alarm, the make-up rate could be restored in steps to the maximum level, according to the strategy outlined in section 3.4.2.2. The programme as completed during the test week is given below.

Table 3.1 *Programme for testing of EARS prototype.*

Week 49.2003			Final test
Su	30.11.03	night	Maintain discharge cycle time at 3.2 hours (weekend regime).
Mo	01.12.03	12:00 AM	Start secondary fuel test (7.5% co-firing); Run EARS; Daily bed sample collection & analysis.
Tu	02.12.03		Run EARS; Daily bed sample collection & analysis
We	03.12.03	8:00 AM	Increase secondary fuel (15% co-firing); Run EARS; Daily bed sample collection & analysis.
Th	04.12.03		Set discharge cycle time to 4.0 hours; Run EARS; Daily bed sample collection & analysis.
Fr	05.12.03		Run EARS; Daily bed sample collection & analysis; Maintenance stop 80 MW_{th} BFB combustor.

3.4.3.2 Test results - overview

During the test week, the sand make-up was reduced by 35% in stead of the 40% planned (corresponding to a final discharge cycle of 4.0 in stead of 4.5 hours). Also, secondary fuel tests were carried out. Overall, neither the testing with secondary fuel nor the substantial reduction of sand make up seems to have caused problematic agglomeration over this one week period. However, it was concluded that the bed might not have been stable for much longer under these conditions. During the week two EARS alarms occurred. No control actions have been initiated.
The sieve analysis of the bed samples collected during the test week were compared with those obtained earlier (October 2002, see also Figure 3.6). Table 3.2 shows that the particle size distribution changed considerably during the test week.

Table 3.2 *Comparison of bed particle size distributions measured during the test week with measurements in October 2002. Numbers are weight fractions in %.*

Size bin [µm]	October 2002	Section 1		Section 2		Section 3		Section 4		Section 5		Section 6	
		S	E	S	E	S	E	S	E	S	E	S	E
400-600	<2	2	<2	2	<2	12	<2	2	<2	2	<2	<2	<2
600-800	2-15	16	11	15	9	16	10	17	12	18	11	14	12
800-1000	20-35	31	27	31	24	29	27	33	30	32	28	31	28
1000-1250	30-50	37	34	36	34	31	35	34	34	33	36	37	35
1250-1600	5-20	9	15	10	16	8	15	9	14	10	14	11	13
1600-2000	<5	<5	7	<5	9	<2	3	2	5	2	6	2	6
2000-2500	<2	<2	<2	<2	<2	<2	<2	<2	<2	<2	<2	<2	<2

S: Start of test week (01.12.03) E: End of test week (05.12.03)

Operating staff stated from visual observations that the bed quality was poor already at the beginning of the week. However, this statement was not confirmed by the sieve analyses and may have been based on the presence of centimeter-size stones and rocks (see Figure 3.24).

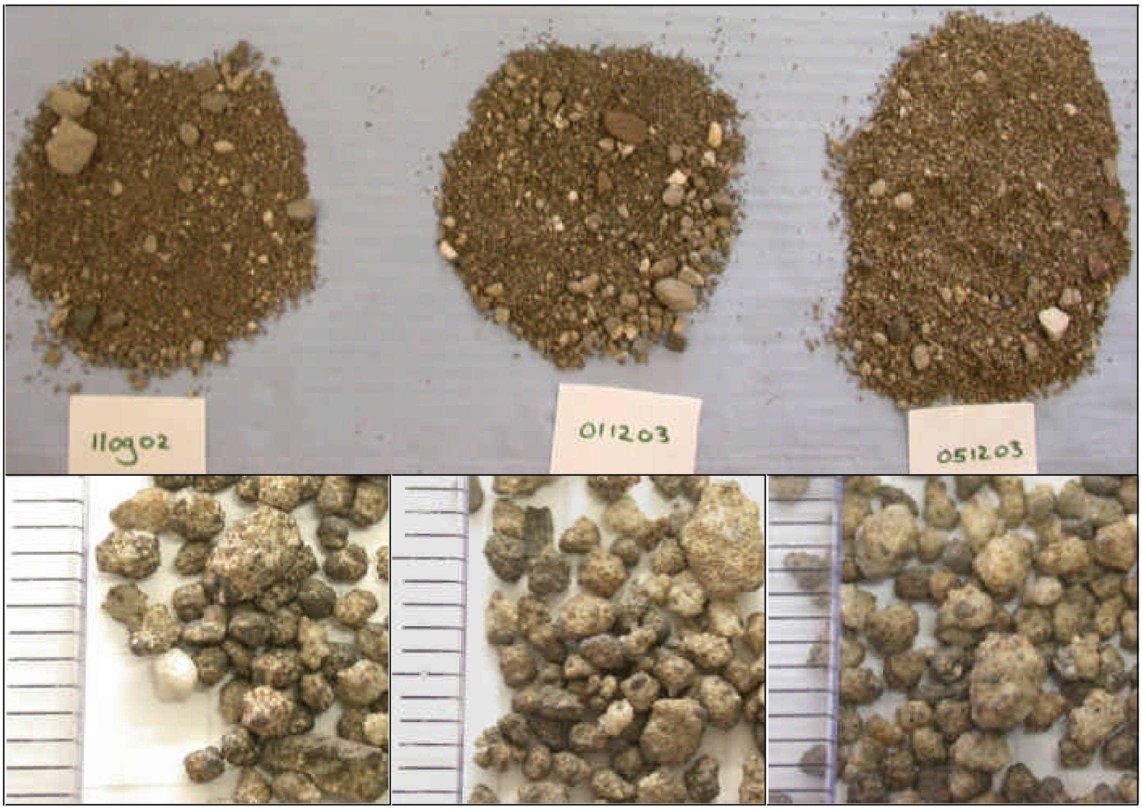


Figure 3.24 *Photos of bed material from the BFB combustor (only particles >1200 µm). Left: 11.09.2002 sample (reference); middle: 01.12.2003 sample (start of test week); right: 05.12.2003 sample (end of test week).*

During the test week, the bed quality deteriorated further by a considerable increase of the fractions of the two size bins, 1600-2000 and 2000-2500 µm. This increase is accommodated by a simultaneous decrease of the fractions of the size bins 600-800 and 800-1000 µm. The shift in particle size distribution was seen in all six bed sections. From the magnifications in Figure 3.24 it is seen that all samples contain small agglomerates and the amount of them seems highest in the 05.12.2003 sample.

3.4.3.3 Test results - quality of measurement

In the weekend preceding the test week, the operation of the combustor was rather instable. This made it difficult to obtain a proper reference preceding the test week. In addition to the low (instable) bed quality to start with, therefore the circumstances for testing were not exactly 'ideal' but could perhaps be called realistic according to industrial standards.

Furthermore, analysis of the pressure measurements indicated that, out of the six positions available, two yielded completely unreliable results (probes 4 and 5), three others were interpreted of medium quality (probes 2, 3 and 6) and only one pressure probe gave high-quality readings (probe 1). In Figure 3.25, position 1 shows a normal power spectrum. The power spectrum of position 2 had a much lower intensity, which means that the signal to noise ratio was low. Plugging of the probe at position 2 has probably caused the decreased intensity. Another problem appeared with *e.g.* measurement position 5, where the power spectrum shows a number of abnormal peaks. When the power plant was stopped at the end of the week, inspection learned that some probes had developed erosion holes which may have influenced the measurements.

However, as will be seen hereafter, the three medium-quality measurement positions have yielded very similar results as the high-quality measurement position, thus confirming the observations for, altogether, four bed sections.

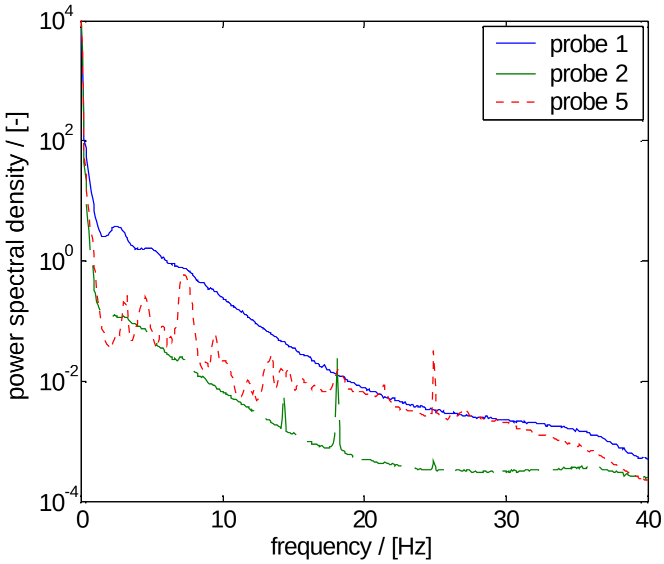
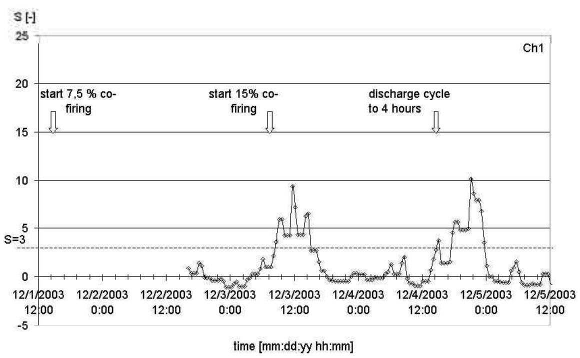


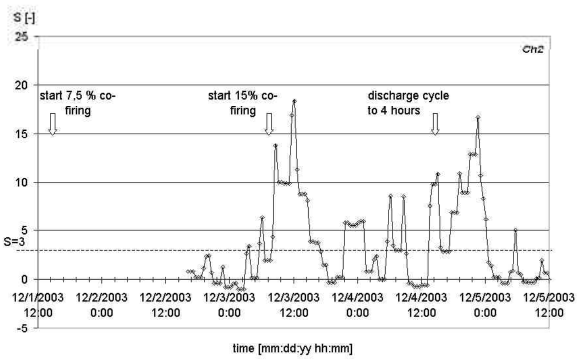
Figure 3.25 *The power spectra for pressure signals measured at three locations during the test week.*

At the moment of the test, with only one measurement position of confirmed high-quality, the pressure measurements were considered not sufficiently reliable to justify active control measures according to the scheme of Figure 3.23. Therefore, the encountered EARS alarms have not been followed-up.

3.4.3.4 Test results - EARS

The *S*-values measured in bed sections 1 (high-quality measurement position) and 2, 3 and 6 (medium-quality measurement position) calculated with a moving reference (24 hour time lag) are shown in Figure 3.26. The corresponding, relevant process data are given in Figure 3.27.





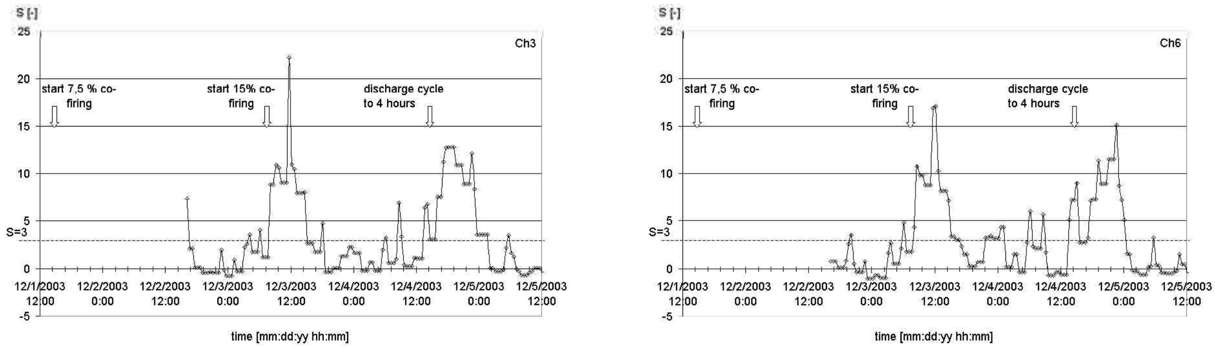
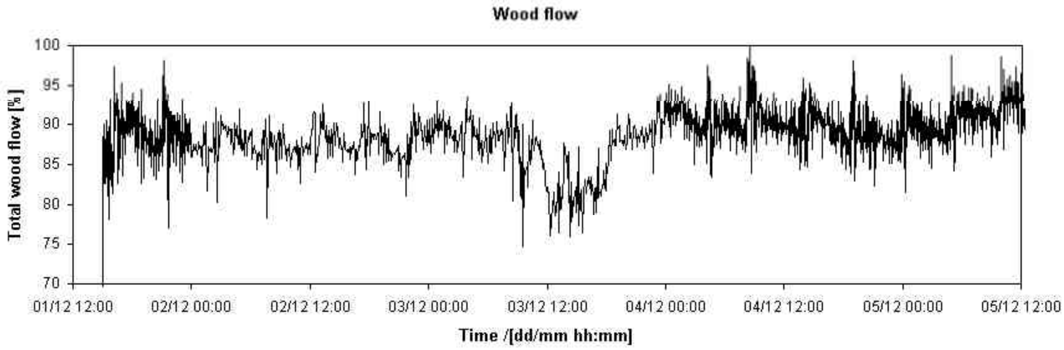
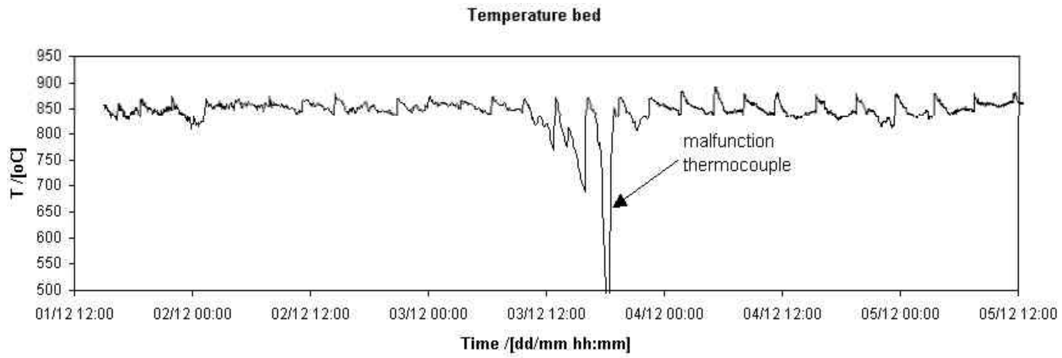
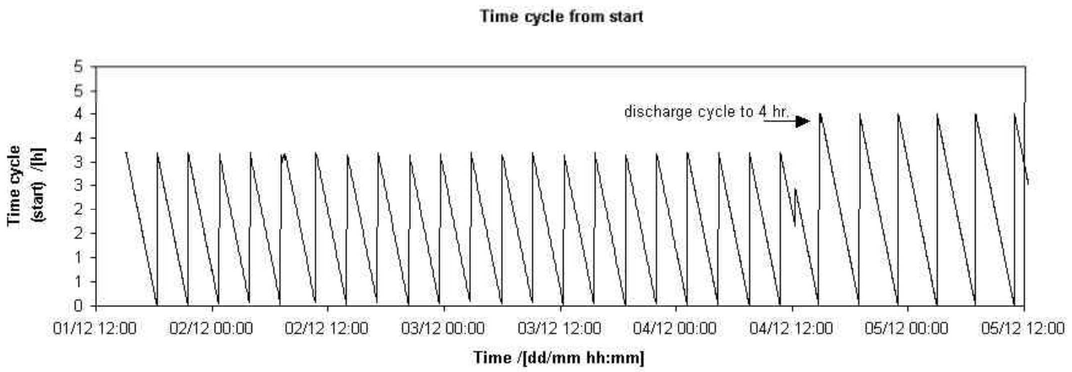


Figure 3.26 *The S-values for pressure probe positions 1 (high-quality measurement) and 2, 3, 6 (medium-quality measurement) during the test week, using a moving reference with a 24 hour time lag.*







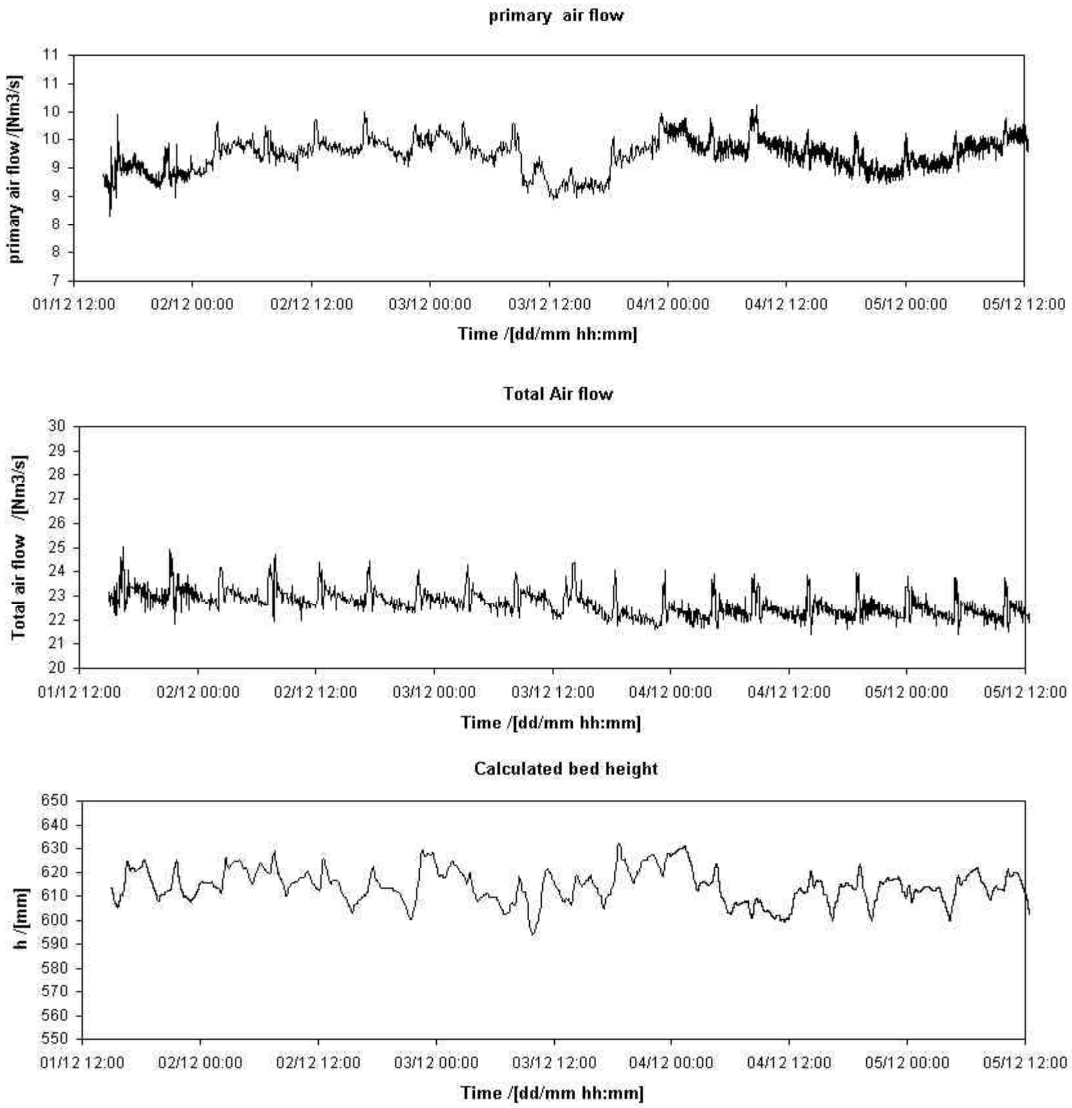


Figure 3.27 *Relevant process data recorded during the test week.*

Measurement position 1 gave alarms (*S*>3, code red corresponding to diagram in Figure 3.23) at two instances, which were confirmed by the medium-quality measurement positions 2, 3 and 6. The first alarm generated by the *S*-values calculated with a moving reference should be interpreted with caution. As explained in section 3.3.2, in case of a moving reference with a 24 hr time lag an alarm will be followed by a second, 'false' alarm 24 h later: at that time the deviation of normal behaviour is enclosed in the reference. Because the moving reference measurement was started at 02.12.2003 - less than 24 hours after the fixed reference calculations caused an alarm - it displays this alarm again, at 03.12.2003. The actual first alarm was caused by an event which took place at 02.12.2003. This effect was also explained in Figure 3.17. The second alarm coincides with the *S*-value if it had been calculated with a fixed reference (Figure 3.28), and is therefore a 'timely' alarm.
The process data in Figure 3.27 cannot explain the EARS alarms, which leaves agglomeration as the only explanation. In order to evaluate this further, the *S*-values based on a fixed reference were compared to the particle size distribution data, see Figure 3.28. When a relation between *S* and the bed particle size is investigated, it is better to use a fixed reference. In that case, the reference can be put at one distinct particle diameter, and an increase in particle size should lead to an increase in the *S*-value.

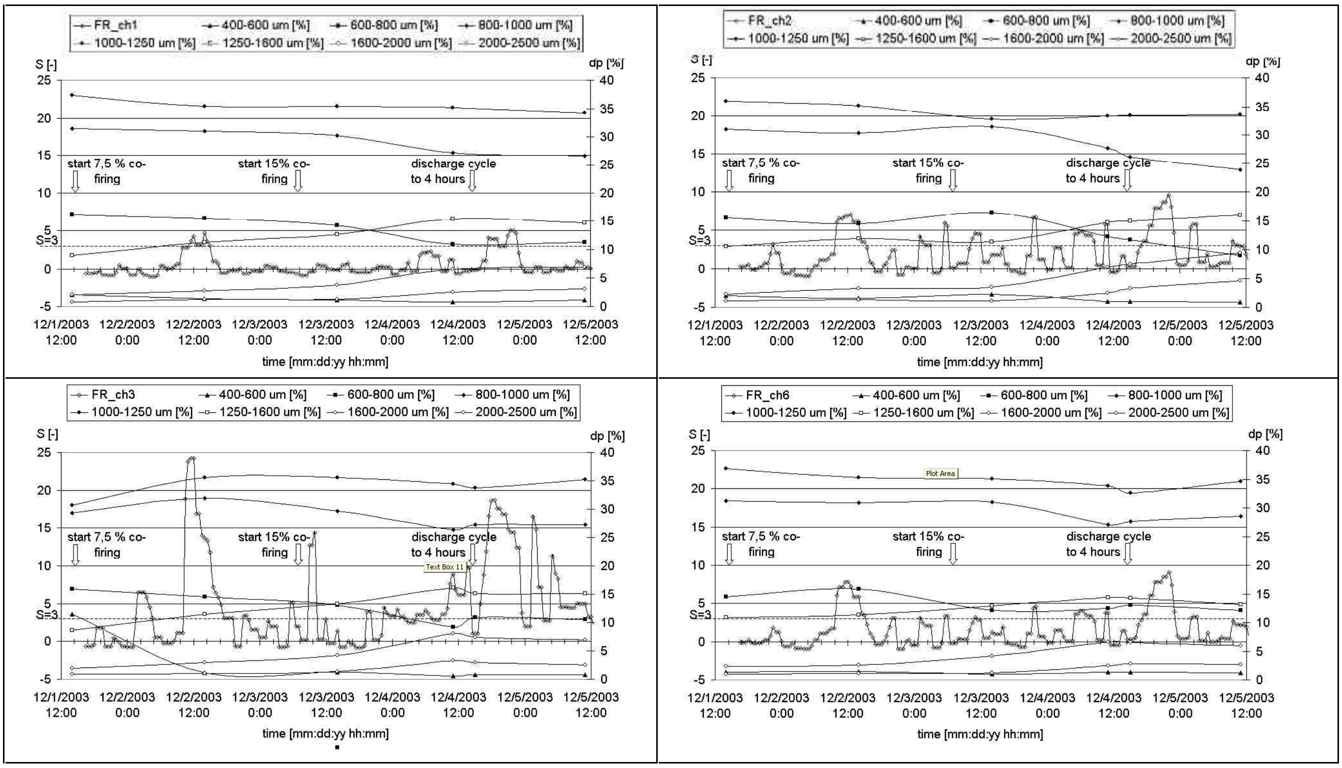


Figure 3.28 *The S-values for pressure probe positions 1,2,3 and 6 during the test week, using a fixed reference (taken at 01.12.2003, time 16:00-16:20h). Included are the corresponding particle size distributions determined by sieve analysis.*

In Figure 3.28 the 04.12.2003 EARS alarm coincides with an increase of the fraction of the two particle size bins, 1600-2000 and 2000-2500 µm, for all four bed sections. In the past, it had already been shown that, indeed, EARS is sensitive for an increase in coarse particle fraction from 0 to 20% [7]. However, that analysis was carried out with evaluation time-series of 5 minutes. Here, evaluation time-series of 30 minutes were used (*i.e.*, a factor 6 longer), which will increase the sensitivity of *S* by approximately $\sqrt{6}$. This shows that the former results are in line with the current results: for the test week the observed changes in the coarse particle fraction with about 5-10 %point are leading to a significant change in *S*.

It was concluded that EARS has successfully detected the significant changes in particle size distribution which have occurred in the bed during the test week. There is no explanation for the return of *S* to a level below 3, on 05.12.2003. Potentially there could be an effect of changing stickiness of bed particles, but this was not proven because no samples were available from the time of the 04.12.2003 alarm.

Being a tool for the early detection of agglomeration, EARS can also be used for process optimisation with respect to sand consumption. During the test week a 35% reduction was accomplished, resulting in a further deterioration of the bed quality and an EARS alarm just before the plant stop. Although no fluidisation problems were concluded, the EARS alarm seems to indicate that problematic agglomeration is upcoming when the discharge cycle time is increased beyond 4 hours. It is not certain whether the process will be stable during prolonged operation at a 4 hour cycle time and more testing is needed to confirm this. Moreover, testing and optimisation of the agglomeration control algorithm is needed. Finally, a better design and operation of the pressure probes are needed to make EARS more reliable: a constant purge flow to prevent plugging and a proper design to prevent probe damage from erosion.

4. EVALUATION AND CONCL USIONS

EARS, a system for the early detection and control of agglomeration in fluidised-bed conversion of biomass, has been tested in the Essent wood-fired, 80 MW_{th} bubbling fluidised-bed combustor in Cuijk. It was already demonstrated on bench-scale that EARS can effectively detect the onset of agglomeration, approximately 30-60 minutes before conventional techniques based on pressure drop or temperature detect it. Moreover, it was shown that EARS is insensitive to variations in fluidising velocity and bed height as encountered in industrial practice. Within this project, it was shown that EARS is not only sensitive to changes in the particle size distribution, but also to changes in the stickiness of bed particles, both key parameters in agglomeration.

In the Essent 80 MW_{th} BFB combustor in Cuijk, a six-sensor EARS prototype was installed and tested. During more than a year, data were collected and analysed to establish a reliable relation between the *S*-values reported by EARS and the agglomeration status of the fluidised bed. In order to accomplish this, the data from 28 process parameters were analysed and, during designated periods, samples of bed material were collected, photographed and sieved. A positive relation was found between the EARS *S*-value and the mass fraction of a particle size considered an indicator for the agglomeration status of the bed. From the process data evaluation it was concluded that even under industrial conditions, EARS is not disturbed by up to 10% variations in the fluidising velocity or bed height. For the remaining process parameters, no relation with the EARS *S*-value was found. The reliability of EARS was greatly increased by filtering out short-duration, false alarms and by the development of a technique using a dynamic reference period. The latter is especially useful to deal with large process variations or if the process is operated under different sets of conditions.

On a bench-scale, the EARS *S*-value was successfully used as a basis for bed quality control; the agglomeration level of a bench-scale bubbling bed combustor could be regulated by means of batch-wise replacement of bed material. It was also shown that, when bed material was replaced, EARS correctly indicated the return of the process to the normal point of operation.

Prior to a planned outage of the Essent installation a similar method of agglomeration detection and control was tested under industrial conditions. During the test week a 35% reduction of the sand make up was accomplished, resulting in an EARS alarm just before the plant stop. Although no fluidisation problems were detected, a further deterioration of the bed quality in terms of the coarse particle fraction was confirmed. The EARS alarm seems to indicate that problematic agglomeration is upcoming when the bed discharge cycle time is increased beyond 4 hours. It is not certain whether the process will be stable during prolonged operation at a 4 hour cycle time and more testing is needed to confirm this. EARS was thus demonstrated to be a useful tool for the detection of agglomeration under industrial conditions.
An algorithm to control the bed discharge and sand make up rates based on the EARS' *S*-values was proposed but not tested in practice, because the quality of the pressure measurements was insufficient at the time of the test. A proper control of the functioning of the pressure measurement probes is essential for continuous monitoring of the agglomeration status.

In order to control agglomeration effectively, the process control algorithm must be validated in practice such that the proposed criteria for warning and alarm can be optimised. It should be noticed though, that for the Essent fluidised-bed combustor, due to the installation of an automated sieve for bed quality control, the bed particle size distribution was much better controlled than before and the make-up of sand was decreased already to a large extent. In this particular case, therefore, an additional decrease using EARS will be small compared to systems without such a sand recycle system.

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