A METHOD TO DETECT AND CONTROL FULLY FLUIDIZED CONICAL BEDS WITH A WIDE SIZE DISTRIBUTION OF PARTICLES IN THE VICINITY OF THE MINIMUM FLUIDIZATION VELOCITY

by

Jernej MELE [a], Iztok GOLOBIČ [b], and Andrej SENEGAČNIK [b*]

[a] Bosio d. o. o., Štore, Slovenia
[b] University of Ljubljana, Faculty of Mechanical Engineering, Ljubljana, Slovenia

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This article presents a new method for the control of a gas-sand conical fluidized bed with a wide size distribution of particles. A two-step procedure was developed and experimentally tested. The minimum velocity for full fluidization is determined by a new statistically based method and then the fully fluidized state is initiated and controlled. It is proven that the characteristics of the pressure drop vs. fluidization velocity remain practically the same for different bed heights and over a wide size distribution of particles. The method analyses the recorded pressure drops with a histogram. The minimum velocity for full fluidization is determined as the smallest fluidization velocity from the histogram bin with the highest density. Finally, it is also proved that the fluidization velocity is a reliable parameter for controlling the fluidization. The method was used to control fully fluidized beds at the minimum gas velocity in a pilot FICFB gasificator.

Key words: *conical fluidized bed, minimal fluidization velocity, process control, parameter identification*

Introduction

Gas-solid fluidized beds are widely applied in chemical processes, combustion, and catalytic gasification, physical processes like the adsorption, heating, cooling, drying and coating of particles, and many more. In processes where the fluidizing agent has a high impact on their overall efficiency, it is of crucial importance to run the process in the vicinity of the minimal fluidization velocity in order to lower the consumption of agent.

In this field of research some of the key studies were conducted by Kwauk [1], Kunii and Levenspiel [2], and Oka [3]; these are basic to an understanding gas-solid behaviour in conical beds. Jing *et al*. [4], Kaewklum and Kuprianov [5], Loffler *et al.* [6] investigated the geometrical characteristics of beds, such as the diameter, height, and cone angle. Girimonte and Formisani [7] investigated and discussed the effects of high temperatures on the minimum bubbling velocity in fluidized beds. There have been a lot of different approaches to the detection and control of the fluidized bed state, with mainly statistical approaches, as described by Johnsson *et al*. [8], Langde *et al*. [9], and Zhang *et al.* [10].

* Corresponding author; e-mail: andrej.senegacnik@fs.uni-lj.si

The mechanism described in the patent by Dziubakowski and Smith [11] is the traditional method for determining the minimum fluidization velocity. It is a system for controlling the bed level of a fluidized bed independently of the density of the bed material and uses the pressure drop across the bed *vs*. the superficial gas velocity. This method is widespread in the industry, because the control of a fluidized bed apparatus can be performed easily, precisely, and rapidly, both manually and automatically. The method relies on multiple pressure sensors.

Statistical methods use time-series analyses of the pressure fluctuations for detection of the fluidization states. The patent JP1168335 [12] describes a method for detecting the state of fluidization in a fluidized bed. The detection procedure compares the values of the fluctuations in pressure with a reference value. In a review, Van Ommen *et al.* [13] indicates that the applicability of such methods is limited.

A few statistically oriented analysis techniques based on pressure signals have been presented since 2000. The method using a Gaussian spectral pressure distribution proposed by Parise *et al*. [14, 15] is based on a spectral analysis of pressure-fluctuation measurements. It can prevent the undesired phenomenon of the partial or complete defluidization of fluidized beds by increasing the gas velocity and provides early and adequate observations of the changes in the hydrodynamics of the fluidized bed [16, 17]. Felipe *et al*. [18] suggest predicting the minimum fluidization velocity of gas-solid fluidized beds by analysing the dominant frequencies of pressure fluctuation. The Puncochar *et al*. [19] method is based on the relationship between the gas velocity and the standard deviation of the pressure fluctuation. The authors verified that this relationship can be considered to be linear for a superficial gas velocity $v_{\mathrm{g}} < 2.5\ v_{\mathrm{mf}}$ and particle Reynolds number Re > 30. A review of more recent statistically oriented methods is given by Van Ommen *et al*. [13]. The influence of high temperature on the minimum fluidization velocity was recently investigated by Jiliang *et al*. [20].

In industrial applications, the gas flow used to fluidize the bed is typically chosen as a function of the desired fluidization state and the required mass and energy balances [2], and not as a function of the minimum gas velocity necessary to fluidize all the particles. In some cases it is very important to run the fluidization at the minimum flow velocity. For example, in our case of the FICFB gasification reactor an increase of the fluidizing agent – superheated steam – results in an almost linear decrease of the process efficiencies [21]. Usually, raw syngas is relatively wet and less than 40% of the injected superheated steam reacts in the chemical process. By optimising the fluidization to a bubbling regime, which runs near the minimum fluidization velocities, the demand for superheated steam and the wetness of the syngas is decreased and the calorific value of the syngas is increased [22, 23]. Control approaches that are based on the use of computational intelligence for a fluidized-bed combustion process were investigated by Čojbašić *et al*. [24]. Adaptive neuro-fuzzy-genetic modelling and intelligent control strategies provide an efficient combination of available expert knowledge with experimental data.

In this paper a new, statistically oriented, discrete method for determining the minimal velocity of full fluidization v_{mff}, regardless of the fluidized bed's material granulation, its height, tapper bed angle and operating temperature, is proposed. The primary interest was to develop a method for controlling the fluidized bed in industrial gasifiers and consequently to minimize the consumption of superheated steam as a gasification agent so as to increase the overall process efficiency. This method is not based on an analysis of the pressure fluctuation, as with previously mentioned methods [12-19]. The proposed method statistically analyses pressure drops at specific, superficial gas velocities to identify a required parameter. This evaluation method is the main novelty in this field of research. It uses a natural phenomenon of a mainly constant pressure drop between the minimum bubbling fluidization velocity and the pneumatic transport velocity to help determine the minimum velocity of the fully fluidized bed. Laboratory and industrial tests have shown that the parameter identification can be relatively precise and reliable.

A novel histogram method

Full fluidization is the regime when all the particles have started to fluidize. It occurs in conical and non-conical beds and/or with a wide size distribution of particles.

To control the fluidization process, reliable physical quantities that can be measured have to be observed. We can measure the pressure drop in uniform time intervals during the increasing and decreasing gas velocity between the minimum and the upper limited velocity. On the basis of experiments we can observe recurring pressure drops *vs*. the gas-velocity characteristics.

The pressure scale is divided into intervals in which all the measured values of the pressure drop are counted and presented in a histogram. When evaluating the measured results with a histogram, the most frequent pressure drop is the pressure $\Delta p_{\rm mff}$. It is precisely that value that is being the most considered. Around $\Delta p_{\rm mff}$ the bed material enters in its fully fluidized state at the minimum possible gas velocity $v_{\rm mff}$.

The proposed method returns $v_{\rm mff}$ at point B marked in figs. 1 and 2, which is the value of $v_{\rm i}$ at the most probable pressure drop $\Delta p_{\rm mff}$.

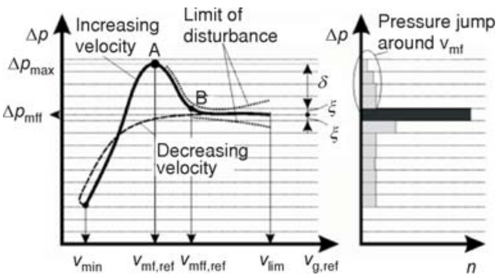

Figure 1. The proposed method for controlling the minimum velocity in a fully fluidized bed in a case with a pressure jump around $v_{\rm mf}$

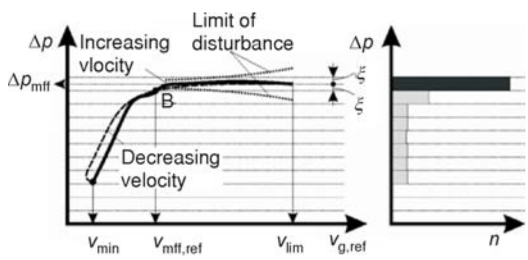

Figure 2. The proposed method for controlling the minimum velocity in a fully fluidized bed without a pressure jump around $v_{\rm mf}$

The measuring protocol takes the pressure drop across the fluidized bed $\Delta p_{\rm i}$ during increasing and decreasing gas velocities from $v_{\rm min}$ to $v_{\rm lim}$ several times. Simultaneously, measured values of $v_{\rm i}$ and $\Delta p_{\rm i}$ are recorded and written mathematically as a point $Z_{\rm i}(v_{\rm i}, \Delta p_{\rm i})$ and collected in a set of points V:

$$V = \{Z_0, Z_1, Z_2, ..., Z_{\rm n}\} \tag{1}$$

From the set of points V, only those $Z_{\rm i}$ points that are within the limits of the histogram bin with the highest density, *i. e*., the pressure drop interval $\Delta p_{\rm mff} \pm \xi$, are taken. The subset of points W is:

$$W \subseteq V \tag{2}$$

$$W = \{Z_{\rm i}\!:\!\Delta p_{\rm i};\ (\Delta p_{\rm mff} - \xi,\ \Delta p_{\rm mff} + \xi)\} \tag{3}$$

There are two cases: with or without a pressure jump around $v_{\rm mf}$, see fig. 1 and 2. If a pressure jump occurs than we have $\Delta p_{\rm max} = \Delta p_{\rm mff} + \xi + \xi$. A pressure jump around $v_{\rm mf}$ is detected by comparing the number of points in several pressure intervals below $\Delta p_{mff} - \xi$ and above $\Delta p_{mff} + \xi$. When approximately the same number of points are in bins above $\Delta p_{mff} + \xi$ and below $\Delta p_{mff} - \xi$, it is assumed that a pressure jump around v_{mf} is present.

Furthermore, the number of successive pressure measurements above $\Delta p_i = \Delta p_{mff} + \xi$ at an increasing gas velocity is counted. A pressure jump J_i around v_{mf} is defined as the subset of V with the largest number of successive elements:

$$J_i = \{Z_i{:}\Delta p_i;\, \Delta p_i > \Delta p_{mff} + \xi \wedge v_i - v_{i+1} < 0\} \tag{4}$$

$$J_{max} = \max\{J_i\} \tag{5}$$

Therefore, Δp_{mf} is defined as the maximum pressure drop Δp_{max} in the set of points J_{max}. Consequently, $\Delta p_{mf} > \Delta p_{mff}$ and a pressure jump $\delta > 0$ is present, see fig. 1. If there is no pressure jump around v_{mf} we have $\Delta p_{mf} \approx \Delta p_{mff}$, which gives $\delta \approx 0$, see fig. 2.

In the case when $\delta \approx 0$ the minimum velocity of a fully fluidized bed v_{mff} is given as the lowest velocity among the points v_i in the subset W. For the minimum velocity of a fully fluidized bed measured at the reference point we have:

$$v_{mff} = \inf\{v(Z_i){:}Z_i \in W; v_i - v_{i+1} > 0\} \tag{6}$$

In the case of a pressure jump, $\delta > 0$, the minimum velocity of a fully fluidized bed v_{mff} is determined among the points that were recorded for an increasing gas velocity in the interval $\Delta p_{max} \geq \Delta p_i > \Delta p_{mff}$. Therefore, a subset T is defined as:

$$T = \{Z_i{:}\Delta p_i;\, (\Delta p_{max}, \Delta p_{mff}) \wedge v_i - v_{i+1} < 0\} \tag{7}$$

The minimum velocity v_{mff} lies among the measured points $Z_i(\Delta p_i, v_i)$ that lie at the intersection of the subsets W and T. The v_{mff} is defined as the minimum velocity in that intersection:

$$v_{mff} = \inf\{v_i(Z_i){:}Z_i(W \cap T)\} \tag{8}$$

The subset T guarantees that v_{mff} was taken from the points which lie just to the right of a pressure jump and not further to the right at higher velocities that could potentially be recorded as random pressure fluctuations.

The question arises: how to determine the size of the pressure interval ξ and how to detect δ. The full size of the pressure interval is 2ξ. If the value ξ is increased, the histogram resolution and, consequently, the probability of a correct Δp_{mff} estimation decrease. However, if δ is increased the opposite effect occurs. When the histogram resolution is lowered the subset W is increased and the interval of v_i becomes wider too. Likewise, the possible v_{mff} is shifted right towards lower values. For a wider v_i interval, the estimation of v_{mff} could be outside of the fully fluidized regime.

Another problem with the pressure-drop values is that after reaching the minimum fluidization state, with an increase of the gas velocity, fluidization goes into the bubbling regime, causing local jumps in the pressure-drop values. Such short-term pressure disturbances should be filtered out. A moving average has been shown to be an effective and proper filtering method. The filtering should not be too strong because the main pressure jump δ needs to be detected, and if the signal is not filtered enough some pressure jumps can be recognised as noise. To distinguish the main pressure jump around v_{mf} from local disturbances the following procedure was used. The pressure jumps can be statistically analysed in short timeframes. Short serial multiple pressure jumps can be described as measure disturbances, while a singular long overpressure area can be identified as a fluidized-bed phenomenon.

Testing of the proposed histogram method

Using this described method of v_{mff} detection, several experiments were performed to test and validate the method. The method has proved to be robust and appropriate for industrial systems like fluidized-bed gasificators, fluidized-bed furnaces, sanding machines, *etc*. In such industrial cases the particles in the bed are never uniformly sized with the same density. One of the goals is to use the minimum possible number of sensors for the control. In our case this is achieved with only two pressure sensors: one for the gas velocity and one for the pressure-drop measurement.

During the development of a FICFB gasifier the aerodynamics and control-governing protocols were tested on a small-scale laboratory unit. In this laboratory unit the histogram method was tested as a detection-control technique. The scheme of the laboratory unit is presented in fig. 3.

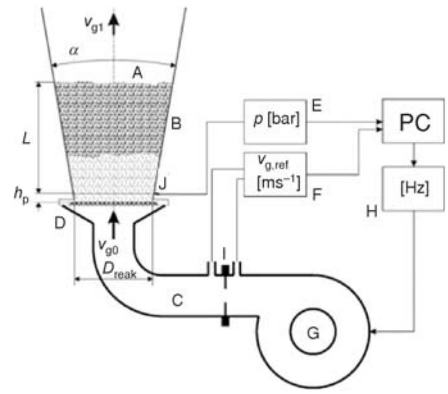

Figure 3. Scheme of laboratory unit with reactor dimensions, A – conical or non-conical bed of particles, B – housing, C – tube, D – distributor, E – relative static pressure measure, G – driving fan, H – power inverter, I – orifice, J – pressure measure opening, PC – personal computer

Figure 4. Laboratory small-scale test model unit for cold testing

The laboratory unit is made of stainless steel with an exchangeable cone housing and with air as the fluidizer, fig. 4. The fluidizing air flow was produced with a high-pressure driving fan, controlled by a variable-frequency power inverter. It is open on top so that the process can be observed. At the bottom of the reactor there is a metal net with 0.2 mm openings. Under it, an 8 mm ceramic wool was installed to prevent the finest bed material from entering the tube.

Monitoring the pressures and temperatures is important for the experimental work. The measuring equipment was an Endress+Hauser PDM75 with the measuring range of 0-1000 Pa ± 1 Pa for the gas flow and a Siemens Sitrans 250 delta bar with the measuring range of 0-100 ± 0.5 mbar for the fluidized-bed pressure-drop measurements. In the case of the pilot FICFB gasifier the temperatures were measured with NiCr-Ni thermocouples (type K) with a measuring range: 0-1250 °C ± 9.4 °C.

Several tests were conducted in conical beds with angles of 0°, 30°, and 50° at different bed heights and at a temperature of ~40 °C. The diameter of the reactor at the bottom of the bed is 300 mm and the diameter of the tube before the air enters the reactor is 100 mm. Tests were conducted with fluidization of the quartz sand with a wide size distribution of particles. The diameters of the particles were between 100 and 900 μm (Geldard B and B/D particles). For each bed height, five cycles of on-line measurements with automatic increasing and decreasing frequency on the power inverter were repeated. The lowest frequency was 5 Hz in all cases. The upper frequency varied between 25 Hz (for thin beds) and 35 Hz (for thick beds). The frequency was increased and decreased with steps of 0.05 Hz/s. The pressure values were recorded every 0.2 s. The control programme counted the differential pressure in predefined intervals. The histograms are presented in figs. 5(b), 6(b), 7(b), and 8. As stated before, the most frequent pressure value is Δp_{mff}. At that pressure interval the controlling programme returned a single value of v_{mff}, which was determined according to the described new histogram method. The obtained results for v_{mff} are converted to the superficial velocities (at the inlet of the particle bed) and marked with diamond points in the characteristic Δp-v_{g}, figs. 5(a), 6(a), and 7(a). The measuring cycles were repeated several times to acquire more representative data.

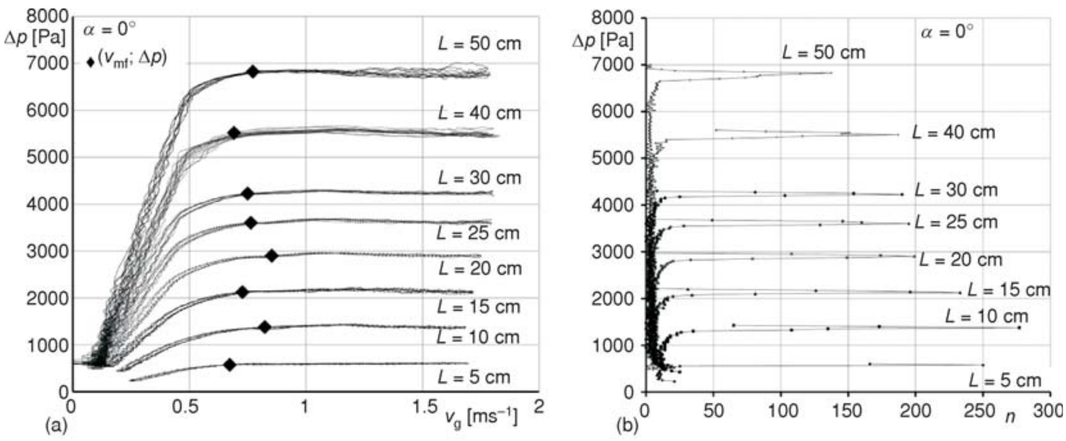

Figure 5. Flow-pressure measurements (a) in 0° conical bed with the histogram (b)

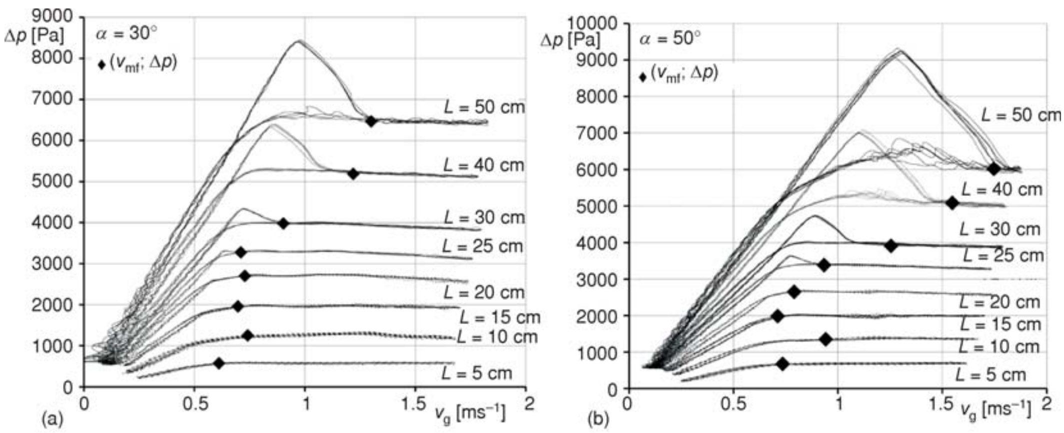

Figure 6. Flow-pressure measurements (a) in 30°conical bed with the histogram (b)

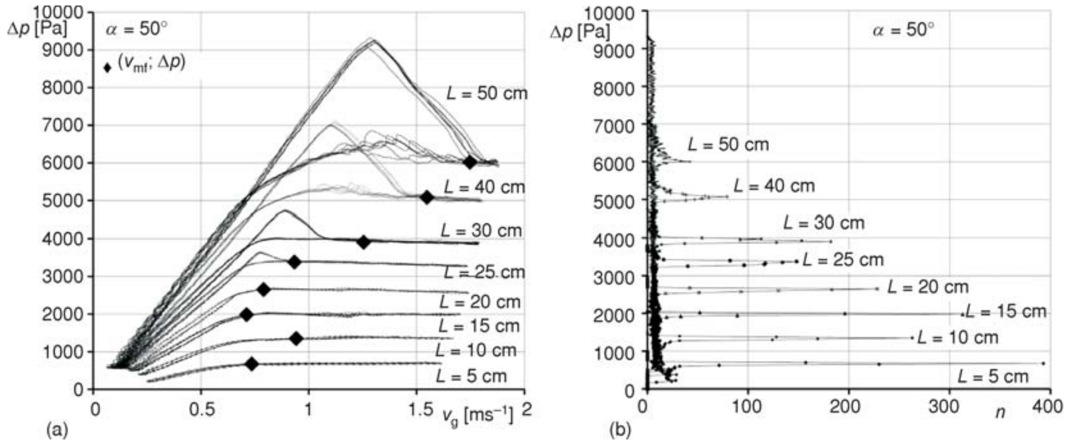

Figure 7. Flow-pressure measurements (a) in 50°conical bed with the histogram (b)

The histogram in fig. 8 shows the detection of a pressure jump around v_{mf}. The data were recorded during the testing of conical beds with α = 30° and bed heights L = 20, 25, and 30 cm. These histograms for different heights are offset by n = 50 at bed heights of 25 cm and 30 cm.

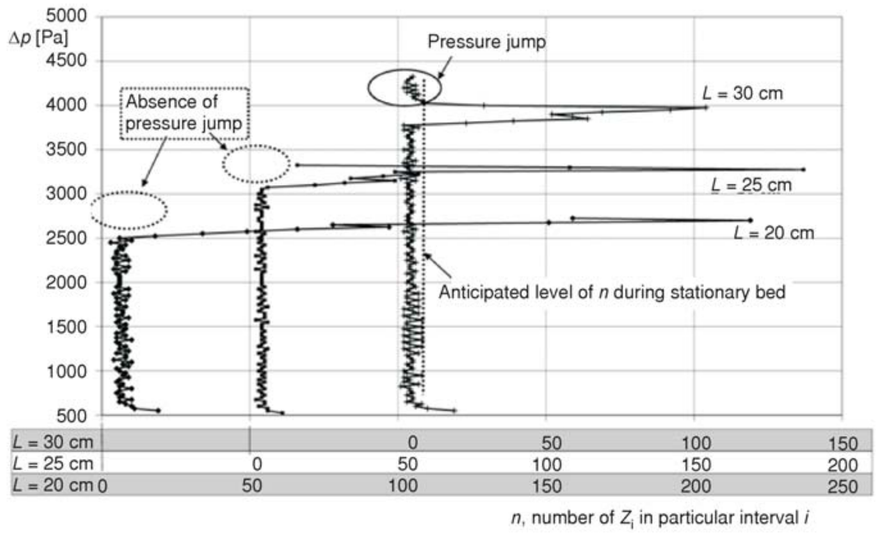

Figure 8. Experimental detection of a pressure jump around v_{mf}

The results in figs. 5(a), 6(a), and 7(a) show that the new histogram method successfully determines the points of minimum fluidization velocity v_{mff}. All of the determined points lie in the region of full fluidization. From the characteristic Δp-v_g diagrams the v_{mff} can also be graphically estimated. The obtained results show that some of the points that are obtained with the histogram method are located at higher velocities than graphically expected. Higher deviations occur in thinner beds and in the cases without a pressure jump around v_{mf}. In cases where a pressure jump is present, v_{mff} is estimated more accurately.

Figure 9. Pilot FICFB gasifier; 1 MW total power

Application of the proposed method in the pilot FICFB gasifier

The method was implemented in the industrial pilot system presented in fig. 9. The reactor bed is conical with α = 40° and with the inlet diameter of 300 mm and approximately 50 cm of bed height. The steam temperature was 670 °C and the gasification temperature in the reactor was 780 °C. The steam generator operates at gauge pressure of 400-450 mbar. Due to the high temperatures in the reactor a bubble-cap-type distributor plate is installed.

For fluidized beds with a wide size distribution of particles (Geldard B and B/D particles) the minimum velocity of its fully fluidized state was determined with the histogram method. The characteristic Δp-v_g diagram recorded during the detection mode is presented in fig. 10. During stable and continuous pilot-plant operation – biomass gasification – slightly higher pressure fluctuations were detected than in the laboratory unit. This is to be expected due to the solid-fuel gasification inside the bed and, consequently, a substantial increase in the volume. The histogram in this case is presented in fig. 11. Because of the wide size distribution of particles like the catalyst, char, particles of solid fuel, ashes, *etc*., there is no pressure jump around v_{mf}. The proposed histogram method successfully detects v_{mff}, marked as a diamond point in fig. 10.

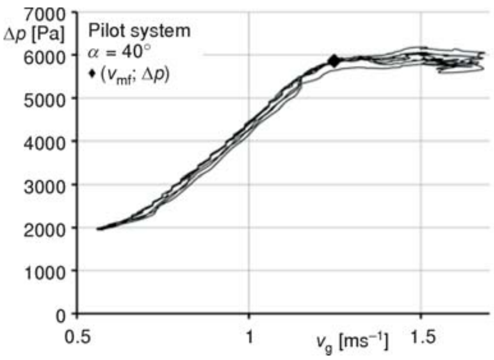

Figure 10. Characteristic Δp-v_g diagram for the pilot reactor; inlet diameter 300 mm, α = 40°, temperature = 670 °C, fluidiser = superheated steam

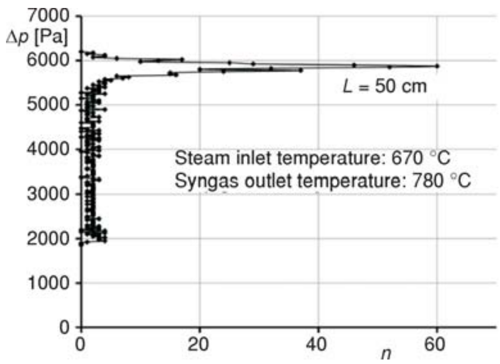

Figure 11. Histogram of initial detection-mode operation of the pilot reactor

Figure 12 presents the time evolution of the starting procedure. The detection mode of v_{mff} lasted approximately 200 s. Three cycles from v_{min} to v_{lim} were made and then the v_{mff} was determined. After reaching the continuous operating mode, the pressure drop and superficial velocity can be observed. The criteria for the pressure drop and superficial velocity deviation can be determined. If after some time of operation the process parameters deviate above/beyond these criteria, the detection mode is repeated and a new operating point is determined.

In the case of a pilot plant, after reaching the operating mode we set the criteria for the pressure-drop deviation to ±10% and likewise for the superficial velocity. If the average value in a time window of 6 s goes above the deviation for more than 10 s, the detection mode is repeated. In practice the process runs at most 30% above v_{mff}, because of the required mass and energy balances in the reactor. Tests have shown that the optimum process parameters are at the stated point.

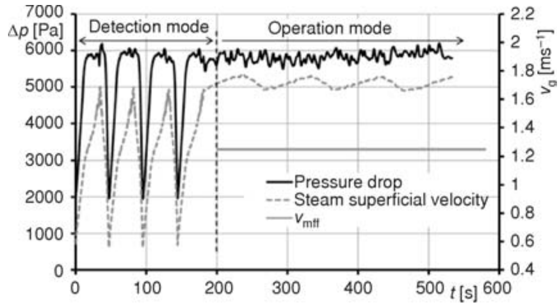

Figure 12. Implementation of the histogram method for the pilot reactor

Conclusions

A new histogram method for the detection of the minimum velocity for a fully fluidized bed is proposed. The method is statistically oriented. The histogram method uses measured data, *i. e.*, bed pressure drop *vs*. fluidization velocity. The minimum velocity of full fluidization is determined as the inferior fluidization velocity of the most frequent pressure drop over the fluidized bed. With this method, occasional pressure jumps around the minimum fluidization velocity are distinguished from the pressure fluctuations. The histogram method was developed on the basis of experimental results. The method has proved to be robust, accurate and reliable. Some deviation occurs for thin beds and in cases without a pressure jump around the minimum fluidization velocity. The research goal was to define and achieve a stationary process on the basis of the pressure drop across the bed *vs*. the gas velocity measurements. The aim was to test the method with a wide size distribution of particles because most industrial processes have this kind of distribution. The method was tested for different taper angles and bed heights. Its reliability and potential for use in industrial systems were confirmed with a successful application in the FICFB biomass gasifier where a lower consumption of superheated steam as the fluidising agent was achieved.

Acknowledgments

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Nomenclature

L – stationary bed height, [cm]
n – number of pressure measurements in specific pressure interval, [–]
p – pressure, [Pa]
V – set of Z_i points
v – superficial gas velocity, [ms^{-1}]
W, J, T – subset of V
Z_i – point with two measured co-ordinates of v_i and Δp_i

Greek symbols

α – conical bed angle, [°]
δ – difference between Δp_{mff} and Δp_{max} [Pa]
Δp – pressure drop, [Pa]
ξ – size of pressure interval [Pa]

Abbreviation

FICFB – fast internally circulating fluidized bed gasifier

Subscripts

g – gas
i – index number
lim – limited value
max – maximum value
min – minimum value
mf – state of minimal fluidization
mff – state of full fluidization at minimal fluidization velocity

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