

## MINIMAL VELOCITY OF FULL FLUIDIZATION – A NEW DETERMINATION METHOD

Jernej MELE, Andrej SENEGAČNIK

### ABSTRACT

*The article introduces the method for characterization and control of fluidized beds with wide size distribution of particles. A laboratory unit has been made for the purposes of experimental research. Our goal is to make an automatic control protocol to find minimum necessary flow of fluidization fluid to run the process at full fluidization. On the basis of measured differential pressure and gas velocity, programme can find the optimal operation area. The method determines a single point among many points with almost same differential pressure and various gas velocities. This method can be used for controlling fully fluidized bed at minimum gas flows in CFB gasifiers, fluidized bed furnaces, fluidized bed sanding machines, etc.*

### NOVA METODA DOLOČITVE MINIMALNE HITROSTI POPOLNE FLUIDIZACIJE

### POVZETEK

*Članek uvaja novo metodo za karakterizacijo in nadzor fluidizirane plasti s široko distribucijo velikosti delcev. Zgrajena je bila laboratorijska enota za eksperimentalne raziskave. Naš cilj je bil izdelati protokol za samodejni nadzor lebdeče plasti in samodejno določitev minimalne hitrosti popolne fluidizacije. Protokol na osnovi izmerjene tlačne razlike in hitrosti fluidizacijskega sredstva določi optimalno območje delovanja. Metoda določi eno točko izmed množice izmerjenih točk s podobnim diferenčnim tlakom in različnimi pretoki fluidizacijskega medija. Metoda je uporabna za krmiljenje lebdeče plasti v primerih ko želimo popolno fluidizacijo ob minimalnem pretoku fluidizacijskega sredstva. To je npr. pri uplinjevalnikih s cirkulirajočo lebdečo plastjo, kuriščih v lebdečem sloju in napravah za peskanje, itd.*

### 1. INTRODUCTION

Catalytic steam gasification is a process for producing high calorific synthesis gas (syngas) from solid Hydrocarbons. Gasifier is divided in two zones – gasification and combustion zone (also called reactor). The basic idea is to produce syngas in reactor only with

superheated steam and no presence of air. Combustion takes place in combustion zone with air. The bed material circulates between these two zones and serves as a heat carrier and a catalyst. It also provides that syngas and flue gas do not mix inside gasifier and exit from reactor separately. Basically we can produce high calorific syngas with almost no amount of nitrogen by using air for combustion. We have a fluidized bed of catalytic material in reactor. Cooled bed material is transported from bottom of the reactor to combustion zone. There is pneumatically transported and reheated. Flue gas and solid particles are separated in cyclone at the end of combustion zone and gathered in siphon. Heated particles in siphon are fluidized and transported back to reactor. Bed material is highly non-homogenous. Beside wide size distribution of catalyst it contains fuel particles, char, ash, etc., with different granularity and density.

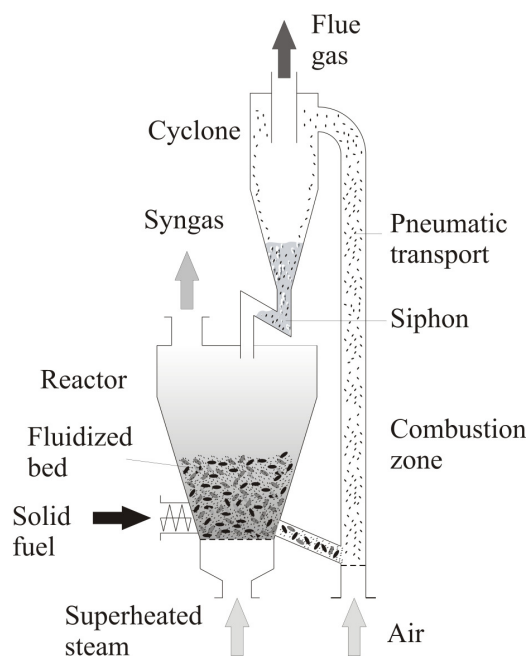


Figure 1: Biomass gasifier

While researching the 750 kW fluidized bed gasification pilot plant certain questions concerning particle dynamics control arose. The question is how to control the fluidized beds in the actual process and how different operating parameters like change of bed height and different granularity of bed material impact fluidization. In mentioned field of research some key studies have been made from Kwauk 1992 [1], Kaewklum and Kuprianov 2008 [2], Jing S. et. al. 2000 [3] etc. Some methods for controlling fluidized beds are also patented. There are two major methods of controlling and detecting the state of full fluidization by comparing the fluctuations of pressure drop in a fluidized bed with a reference value, using a minimum number of pressure sensors. These methods are based on operator experience and constant human supervision and monitoring. Fluidization control is frequently problematic and based on operator experience or trial and error rather than effective monitoring.

In industrial applications the fluidization flow is typically chosen as a function of the desired fluidization state and the required mass and energy balances [4], not as a function of the minimum flow necessary to fluidize all the particles. By biomass gasification with superheated water steam it is highly important to run the fluidization with a minimum steam flow. The chemical activity and efficient of the gasification is almost in linear proportion with the amount of water steam in reactor [5].

In this paper we introduce a new method to characterize fluidized bed parameter  $v_{mff}$  – minimal velocity of full fluidization in reference point.

## 2. LABORATORY TEST UNIT

We have designed a laboratory test unit (e.g. Figure 2) to create a fluidized quartz sand conical bed by blowing the air at different gas velocities. Air flow was forced with a high-pressure ventilator, controlled with a variable frequency power inverter. The main purpose of the laboratory unit is to provide the process of fluidization with a wide size distribution of particles. The unit is left open on top so that the process can be observed, Fig. 2.

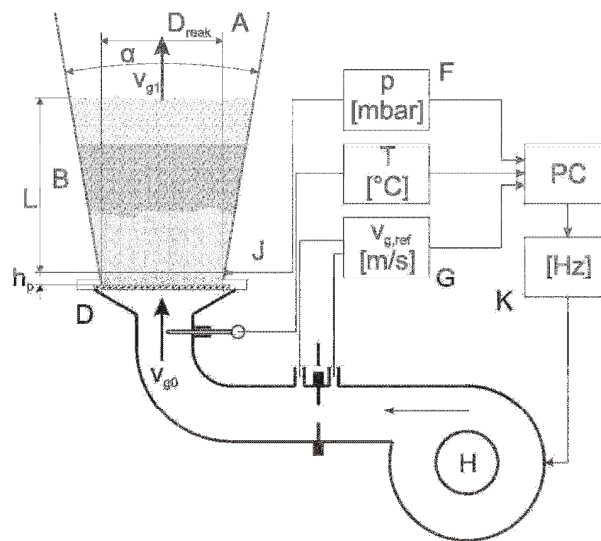


Figure 2: Scheme of laboratory unit with sensors

Conical bed of particles in chamber (A), housing (B), distributor  $\phi 300$  mm (D), air velocity measure (G), high pressure fan (H), orifice (I), pressure measure opening (J), power inverter (K) and PC.

### 3. BASIC CHARACTERISTIC OF FLUIDIZATION

#### 3.1 Minimal fluidizing velocity

For the case of conical bed and/or particles with wide size distribution, clear minimum fluidization velocity is difficult to determine because a part of the bed is fixed whereas the other part starts to fluidize. However, clear minimum fluidization velocity at some reference point in front of reactor can be determined at each bed height. The difference in minimum fluidization velocity among different bed height is considered to be responsible to the tapered design of reactor; higher gas velocity at the bottom  $v_{g0}$  is required to attain fluidization state in the whole bed with high bed height because the gas velocity in the upper part  $v_{g1}$  is lower than that in the bottom bed.

#### 3.2 Pressure drops

Pressure drops  $\Delta p_i$  across the bed versus gas velocity has very characteristic course and is shown in Fig. 3 and 4. For basic  $\Delta p_i$  evaluation a modified Ergun's equation can be used [4]. Pressure drop starts to increase reaching its maximum value  $\Delta p_{mf}$  at minimum fluidization velocity  $v_{mf}$ . At this point only a part of the bed is fluidized. When the bed is fully fluidized, at  $v_{mff}$ , the pressure drop is reduced to  $\Delta p_{mff}$  and is almost constant until the gas reaches terminal velocity  $v_t$  [2]. If the velocity is still increasing, the particles start transporting pneumatically and the pressure drop reduces rapidly towards 0.

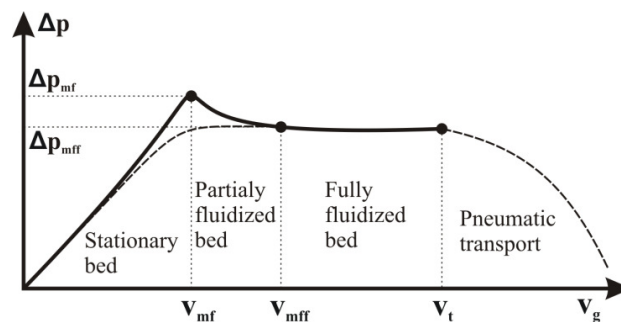


Figure 3: The change in pressure drop relative to gas velocity for Not-too-Small Uniformly Sized Particles [4]

A somewhat different differential pressure characteristic occurs with a wide size distribution of particles, which are usually present in industrial processes. When the gas velocity increases through the bed of solids, the smaller particles start to fluidize and slip into the void spaces between the larger particles, while the larger particles remain stationary [1], [2], [3] (e.g. Figure 4). However, after a full fluidization of bed material ( $v_g > v_{mff}$ ), with increasing air velocity, pressure drop mainly remains constant.

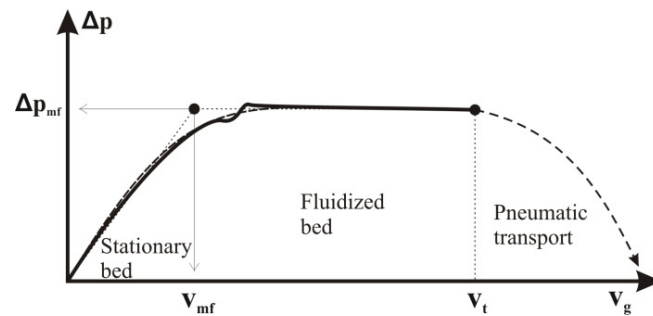


Figure 4: The change in pressure drop relative to gas velocity for Wide Size Distribution of Particles [4]

Pressure drop through the fluidized bed is measured at the bottom of the bed and just above ( $h_p$ , Fig. 2) the distributor. With the experiment has been proven that the characteristic shape of pressure drop always remains the same with the increase of flow velocity through the fluidized bed, also at different bed heights and wide distributed particles sizes. This characteristic shape can be a reliable parameter for controlling the process.

#### 4. EXPERIMENTAL WORK

On the basis of the above mentioned knowing the experiment was performed. As a bed the quartz sand was used. Diameter of sand particles ( $D_p$ ) is between 100 and 900  $\mu\text{m}$  with density ( $\rho_p$ ) of 2560  $\text{kg/m}^3$ . Bulk density is 1575  $\text{kg/m}^3$  and voidage for fix bed mode is 0.594.

A series of measurements were made with different bed heights and different cone angle. Fig. 5 illustrate the influence of different bed heights on pressure drop at various air velocities from some minimal value to some maximal value and back to minimum in a case of a 30° cone reactor. Cycles may be repeated several times to acquire more representative data.

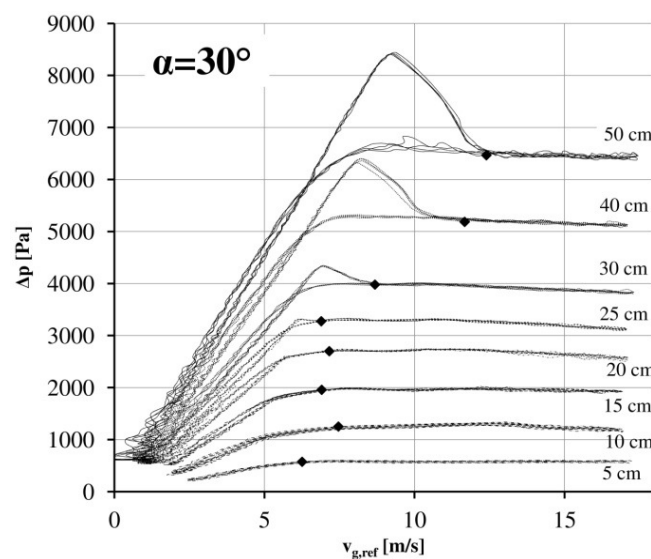


Figure 5: Pressure drops over fluidized bed with increasing and decreasing air velocity at different bed heights in a 30° conical bed

## 5. DETERMINATION OF MINIMAL VELOCITY OF FULL FLUIDIZATION – A NEW APPROACH

In Figure 6 a comparison of our new method to other known methods is presented (see also Fig. 3 and 4). Point A is the proposed point of minimum velocity of full fluidization by several authors. We know that at point A bed material is not fluidized all across the reactor [1], [2], [3] and gas velocity has to increase by some value to achieve full fluidization. Our method returns  $v_{\text{mff,ref}}$  at point B. Gas velocity values returned by our method are always higher than those suggested by other methods. Therefore, gas velocity returned by our method is the most likely velocity of full fluidization  $v_{\text{mff,ref}}$ .

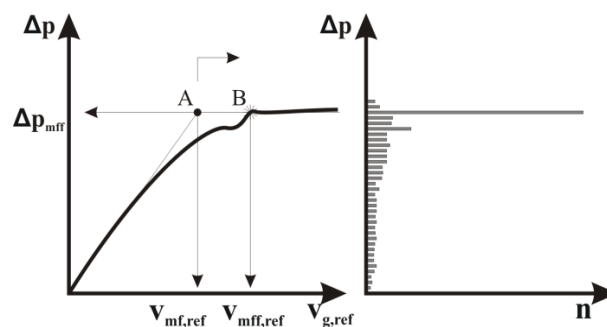


Figure 6: Method for controlling the system and comparison of new approach to previous methods for Wide Size Distribution of Particles

The pressure scale is divided into intervals in which all pressure measurements are counted and presented in a bar graph. When evaluating the measured results with a bar graph (e.g. Fig. 6), the most frequent pressure value is the pressure  $\Delta p_{\text{mff}}$ . Precisely that value is the one we consider the most and around that value bed material enters in its fully fluidized state at minimum possible velocity  $v_{\text{mff,ref}}$ .

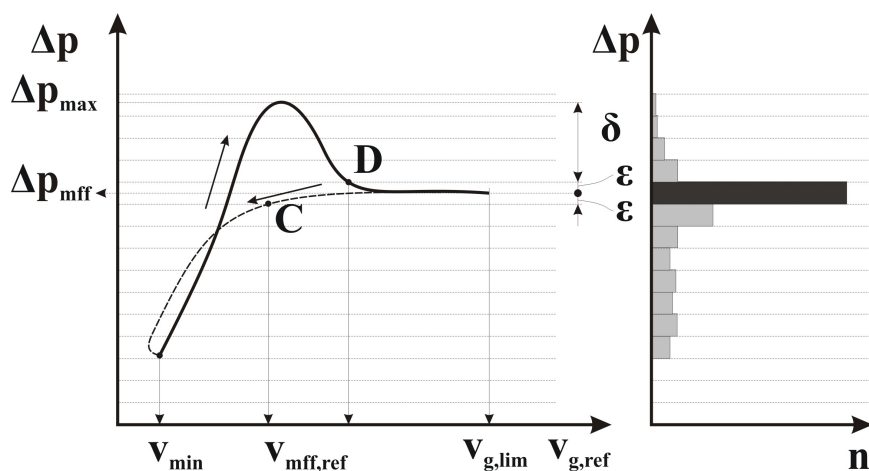


Figure 7: Determination of the minimal velocity of full fluidization, point C or D

Fig. 7 shows the basic idea of the minimal velocity of full fluidization  $v_{\text{mff,ref}}$  determination. In a cases when the pressure jump  $\delta$  occurs point D should be taken, otherwise

point C determines the  $v_{\text{mff,ref}}$ . The "sensitivity" parameter  $\varepsilon$  is arbitrary selected by operator's experience. Presence of the pressure jump  $\delta$  can be detected from bar chart automatically.

The  $v_{\text{mff,ref}}$  determination algorithm can be mathematically expressed as follows:  
After several scans from  $v_{\text{min}}$  to  $v_{\text{lim}}$  and back all of the measured values i.e. pairs  $Z_i(v_i, \Delta p_i)$  are gathered in a set of points  $V$ . Superscript + denotes, that values  $Z_i^+(v_i, \Delta p_i)$  were recorded when velocity  $v_i$  was increasing  $v_{i+1} > v_i$  and vice versa for superscript -.

$$V = \{Z_i\} = \{Z_0^+, Z_1^+, Z_2^+, \dots, Z_{n-2}^-, Z_{n-1}^-, Z_n^-\} \quad (1)$$

The pressure jump  $\delta$  can be detected from bar graph, Fig. 8. The pressure jump  $\delta$  occurs only then when the levels of bar intervals above the most frequent bar  $\Delta p_{\text{mff}}$  are similar to anticipated levels of bars below the  $\Delta p_{\text{mff}}$  i.e. to the level in the stationary bed. For bars which are above the  $\Delta p_{\text{mff}}$  and have higher level than anticipated below level can be concluded that this bars represent noise or common oscillations around  $\Delta p_{\text{mff}}$ , when scanning partially and fully fluidized area. For low bed heights the pressure jumps do not occurs and the bar graph ends just few intervals above  $\Delta p_{\text{mff}}$ , Fig. 8.

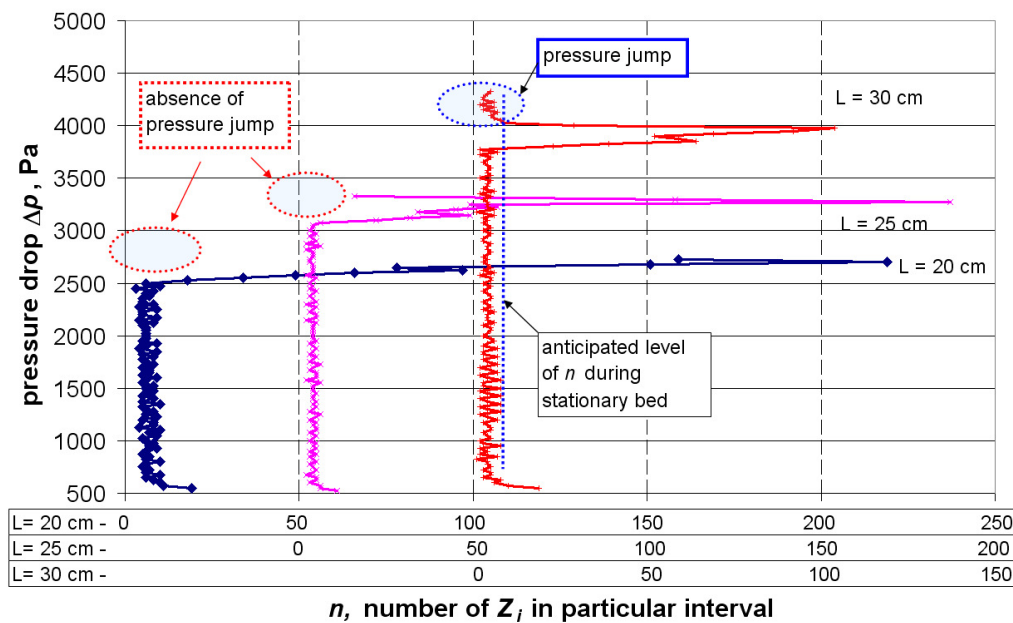


Figure 8: Detection of pressure jump, bar graph for curves from Fig. 5

In a case when there is no pressure jump the velocity at point C (Fig. 7) is taken as the minimal velocity of full fluidization  $v_{\text{mff,ref}}$ . We should find the most left point C on the lower edge of interval  $\Delta p_{\text{mff}} \pm \varepsilon$ . Due to right-left scan hysteresis we should choose just among points  $Z_i^-(v_i, \Delta p_i)$  i.e. points which were record when the velocity was decreasing.

$$v_{\text{mff,ref}} = \inf \left\{ v(Z_i)^- : \Delta p_i \approx \Delta p_{\text{mff}} - \varepsilon \right\} \quad (2)$$

The notation  $\Delta p_i \approx \Delta p_{\text{mff}} - \varepsilon$  means that we should find a point C inside the interval  $\Delta p_{\text{mff}} \pm \varepsilon$  in the vicinity of the interval's lower boundary where it's closest left point  $Z_i^-$  lies already outside the interval.

In a case with pressure jump  $\delta$  the velocity in point D should be taken as the minimal velocity of full fluidization  $v_{\text{mff,ref}}$ . As a point D the first point inside interval  $\Delta p_{\text{mff}} \pm \varepsilon$  after the pressure peak should be taken. Due to left-right scan hysteresis we should choose just among points  $Z_i^+(v_i, \Delta p_i)$  i.e. points which were recorded when velocity  $v_i$  was increasing.

$$v_{\text{mff,ref}} = \inf \left\{ v(Z_i)^+ : \Delta p_i \approx \Delta p_{\text{mff}} + \varepsilon \cap \forall \in [\Delta p_{\text{max}}, \Delta p_{\text{mff}} - \varepsilon] \right\} \quad (3)$$

Where maximal pressure drop  $\Delta p_{\text{max}}$  is

$$\Delta p_{\text{max}} = \sup \left\{ \Delta p_i(Z_i) : Z_i \in V \right\} \quad (4)$$

The notation  $\Delta p_i \approx \Delta p_{\text{mff}} + \varepsilon$  means that we should find a point D at the vicinity of the interval boundary and still inside interval  $\Delta p_{\text{mff}} \pm \varepsilon$ , but it's closest left point  $Z_i^+$  lays already outside the interval.

Above algorithm was applied on values presented in Fig. 5. For different bed heights the points of minimal velocity of full fluidization  $v_{\text{mff,ref}}$  were evaluated. Points of  $v_{\text{mff,ref}}$  are marked with bullets.

Using this method for characterization of parameter  $v_{\text{mff,ref}}$  we have set up several experiments to validate quantitatively and qualitatively gathered end results. This method is very robust and appropriate for industrial systems because there are almost never uniformly sized particles with the same density inside the chambers and reactors. At the beginning of our research [7] we followed previously proposed methods from US4593477 patent by Dziubakowski and Smith, Saxena and Vogel [8], T. Shirai [9] but after some time of experimenting we gave up on them, because they were too precise and delicate. Every change of conditions had a high impact on them and they were therefore unreliable in industry. We needed something more reliable, for different bed materials and conditions.

## 6. CONCLUSIONS

In this article two findings are presented. First a method for fluidized bed characterisation has been developed and tested. It was in our interest to experiment with a wide size distribution of particles because most of industrial processes have this kind of distribution and it seemed wise not to idealize the conditions too much. Second we solved the problem of how to identify the process and then provide efficient control.

Since our method is statistical its accuracy increases with taken samples. The method is quite robust, accurate and reliable.



## 7. REFERENCES

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## AUTHORS ADDRESS:

Jernej Mele, Bsc.Mech.Eng.,  
Bosio d.o.o.,  
Obrtniška cesta 3, SI-3220, Štore, Slovenia

Assoc.Prof.Dr. Andrej Senegačnik,  
Faculty of Mechanical Engineering,  
Aškerčeva 6, 1000, Ljubljana, Slovenia

E-mail: [andrej.senegacnik@fs.uni-lj.si](mailto:andrej.senegacnik@fs.uni-lj.si)