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ADAPTED METHOD FOR DETERMINING THE MINIMAL FLUIDIZATION VELOCITY OF A GAS-SOLID FLUIDIZED BED BY USING AN ELECTRICAL CHARGE SENSOR

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Abstract. *The minimum fluidization velocity is an important parameter for controlling the particle fluidization process and for the development of fluidization equipment itself. In this work, an adaptation of the method used by Puncochar et al. (1985) to determine the U_{mf} of a bed of particles has been proposed. In the proposed method, the velocity of the gas surface was represented by a logarithmic scale instead of linear. Also, the modified method of Puncochar et al. (1985) was applied through a new approach, based on the use of non-intrusive electrical charge sensors. The evaluation of the proposed methods occurred through the comparison of the results obtained with the result of the classic method, presented in Kunii and Levenspiel (1991), and through the results obtained by applying the method of Puncochar et al. (1985), in its original form. The results obtained by the proposed methods proved to be promising since the value of the U_{mf} resulting was close to the results obtained by the method used as a basis of comparison. However, the result obtained, even though it was the closest, was 94.4% higher than the minimum value of the fluidization velocity obtained through mathematical modeling of the bed.*

Keywords: *fluidized beds, electric charge sensors, minimal fluidization velocity*

1. INTRODUCTION

Gas-solid fluidized beds occur when a vertical and upward gas flow passages through a bed of solid particles, generating the so-called fluidization when such mixture behaves as a fluid. Fluidized beds have advantages by promoting good gas-particles mixing, which leads to high rates of heat and mass transfer and temperature uniformity (Kunii and Levenspiel, 1991).

Therefore, fluidization is a complex phenomenon, and the development of techniques for monitoring fluid dynamics can ensure the efficiency and quality of the process (Sun and Yan, 2016). In that sense, there are based those based on the analysis of pressure fluctuations (Schaffka *et al.*, 2015 and Wang *et al.*, 2017b), acoustic and vibrational (Li *et al.*, 2011), capacitance (Chandrasekera *et al.*, 2015 and Weber and Mei, 2017) and electrical charges (Zhou *et al.*, 2013; Chen *et al.*, 2014; Zhang *et al.*, 2016; Yang *et al.*, 2017 and Zhang *et al.*, 2017).

The use of electrical charge sensors in industrial environments is a promising technique since it allows the measurement of different quantities associated with the fluidized bed: the distribution and velocity of the particles (Krabicka and Yan, 2009), and the volumetric global and local concentration of particles (Thuku *et al.*, 2014; Zhang *et al.*, 2017). Such sensors are robust, have low time response, and even installation costs. Also, different characteristics associated with the flow can be studied by signal analysis techniques.

The minimum fluidization velocity, U_{mf} , is one of the most important parameters related to a fluidized bed (Yang, 1998). U_{mf} can be obtained through the diagram $\Delta p_L \times U_g$ (traditional method), described in Kunii and Levenspiel (1991), where Δp_L corresponds to the pressure drop across the bed and U_g the superficial gas velocity, Eq. (1):

$$U_g = \frac{4Q}{\pi D^2} \quad (1)$$

where Q is the volumetric gas flow rate and D is the internal diameter a circular section riser. Fig. 1 shows the $\Delta p_L \times U_g$ diagram of a bed composed of silica sand bed of particles with a uniform size distribution of diameter about 160 μm .

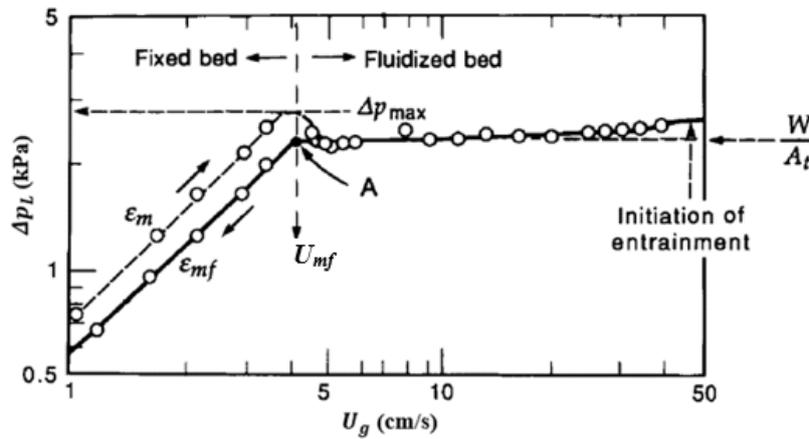


Figure 1. Diagram $\Delta p_L \times U_g$ of fluidized bed composed of air and particles of silica sand with a diameter $d_p = 160 \mu\text{m}$. Adapted from Kunii and Levenspiel (1991).

In Fig. 1, which is called the characteristic curve of the fluidized bed in literature, there is a vertical dashed line indication U_{mf} that divides the graph into two main regions: fixed bed and fluidized bed. From static condition with $U_g = 0 \text{ m/s}$ and by gradual increases of U_g , Δp_L increases proportionally with U_g throughout the so-called fixed bed regime (inclined dashed line), until it reaches a maximum value equal to Δp_{max} (Kunii and Levenspiel, 1991). The value of Δp_{max} should be slightly higher than the pressure drop on the fluidized bed if the particulate material has been compacted before the fluidization test or if it is deposited in a narrow riser (Geldart, 1986). From this condition, a small increase in U_g provokes a sudden decrease in the void fraction of the bed from ϵ_m to ϵ_{mf} , and the pressure drop falls from Δp_{max} to the ratio between bed weight, W , and cross-sectional area of the riser, A_t . Under this condition, the bed regime is called incipient or minimum fluidization. During the fluidized bed regime, Δp_L is almost constant. On another way, by decreasing U_g from the fluidized bed, Δp_L is constant and, after u_{mf} , it decreases progressively until the bed turns back to the static condition (Kunii and Levenspiel, 1991). Therefore, the value of U_{mf} can be determined by regarding the intersection point by the prolongation of the inclined straight line for the fixed bed, obtained by successive U_g decrease, and the line of constant $\Delta p_L = W/A_t$ (Kunii and Levenspiel, 1991), point A in Fig. 1.

Alternatively, U_{mf} can be determined as proposed by Puncochar *et al.* (1985), which is based on the relationship between σ_{pT} and U_g , where the σ_{pT} is the standard deviation of the fluctuation signals of the total pressure across distributor and fluidized bed under different flow conditions, which should be approximately linear in the region of $U_g > U_{mf}$, as shown in Fig. 2 (Puncochar *et al.*, 1985).

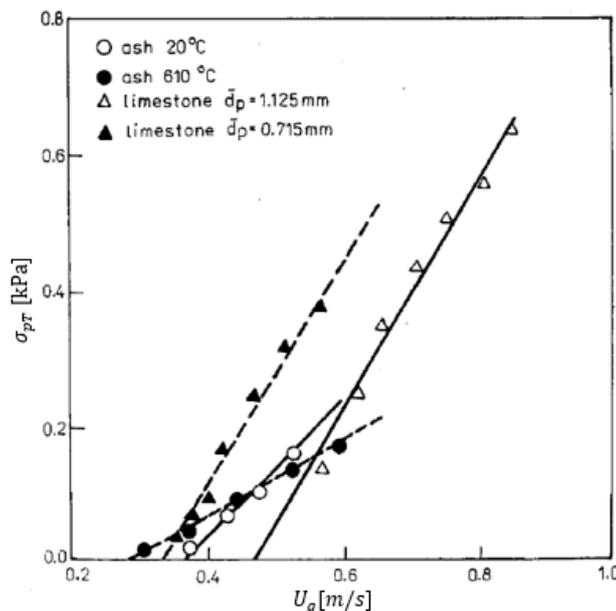


Figure 2. Diagram $\sigma_{pT} \times U_g$ for the determining U_{mf} . Adapted from Puncochar *et al.* (1985).

In Fig. 2, both axes are on a linear scale. The value of U_{mf} can be determined by prolongation the straight line until it cuts the horizontal axis with σ_{pL} (Puncochar *et al.*, 1985). As an advantage concerning the method described by Kunii and Levenspiel (1991), for the method proposed by Puncochar *et al.* (1985) is only necessary to measure total pressure fluctuations at the plenum region, above the distributor of the fluidized bed.

In this work, a method for determining the minimum fluidization velocity is proposed. It is based on that of Puncochar *et al.* (1985) and is applied on both acquired signals of pressure fluctuation at the plenum, and from a ring-type electrical charge sensor from a cold air-silica sand fluidized bed where used. The evaluation of the proposed method was carried out by comparing the results with that by using the standard method presented in Kunii and Levenspiel (1991) and through the results obtained by the method of Puncochar *et al.* (1985).

2. EXPERIMENTAL BENCH AND METHODOLOGY

Figure 3 shows the fluidized bed bench. The air came from a compressed air line at 809 kPa. It passed through a pressure regulator (PR), and a ball valve (OV) used for blocking the airflow. Downstream there was a control valve (CV) and an electronic gauge pressure transducer (PG) from SensynTM, model PTC-102. A laminar flow meter (FM1) measured the airflow rate in the lower range, and an orifice plate meter (FM2), designed according to ASME MFC-14M 2003, in the higher range. They were connected to a differential pressure transmitter (PT1) from RosemountTM, model 2051. An industrial bulb thermometer (TG) measured the airflow temperature.

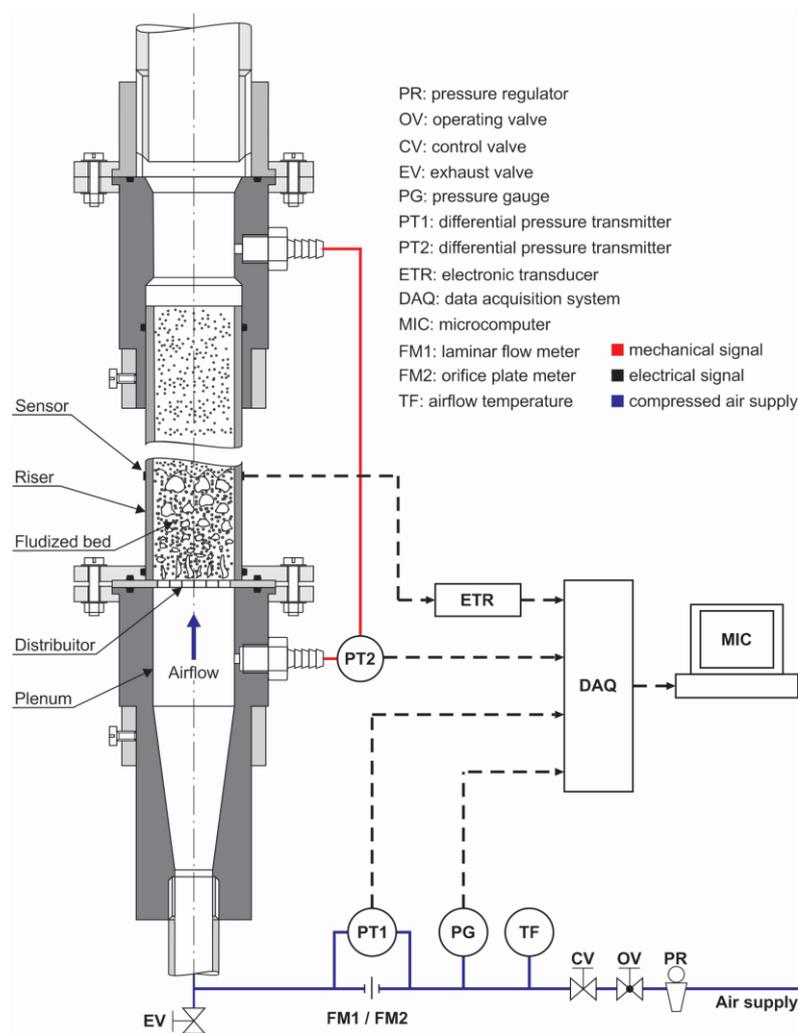


Figure 3. Diagram of the experimental bench.

The air entered in a “T” and flows to upward initially through a 1.2 m of a ½ in straight pipe section, reaching a smooth conical section before the plenum region just below the distributor (perforated plate). This arrangement allowed a uniform gas flow of gas through the distributor.

For acquiring the pressure fluctuation at the plenum, a piezoresistive differential pressure transducer, (PT2) from Rosemount™, model 2051, was connected between the plenum region and the top of the riser, which was made of a $D = 34$ mm Plexiglas pipe section of 950 mm in length, which allowed visualization of the gas-solid flow.

A non-intrusive ring-type electrical charge sensor was installed on the external surface of the Plexiglas pipe, at 100 mm above the distributor. It was connected through a coaxial cable to the electronic transducer (ETR) input. The sensor was made of a 0.06 mm thick copper sheet, having 5 mm of width and 126 mm of length. A grounded metallic shield was used to prevent external interferences.

The electronic transducer ETR was designed with an adjustable gain of 3.3, 33, and 100, which was chosen during preliminary tests as in Tab. 1 for the best sensitivity, and still avoiding saturation of the output amplification stage.

The outputs of PT1, PT2, PG, and ETR were connected to the data acquisition system (DAQ) input, operating with a microcomputer (MIC) with LabView 7.0 software from National Instruments™.

A mass of 0.1302 kg of silica sand was used as the bed inventory, which had a Sauter diameter of 0.306 mm and an apparent density of 2520 kg/m³. During the experiments, U_g ranged from 0.015 to 1.716 m/s regarding 45 test points as shown in Tab. 1, allowing distinct fluid dynamic conditions from static to turbulent fluidization regimes. For choosing the U_g values in Tab. 1, the whole capacity of the bench flow meters was regarded. The intervals between each pair of test points were taken according to a logarithmic scale, allowing the points to be equally spaced on the characteristic curve of the bed, due to the axis of U_g be on a logarithmic scale. In Tab.1, all 45 points were tested by increasing U_g , while points from 29 to 1 were tested on decreasing U_g .

There were distinct absolute pressures (P_g) in the airflow at FM1 or FM2, and in airflow at the riser. Therefore, the airflow rate was measured by FM1 or FM2 had P_g measured by PG and t_g in [°C] by TG, which was converted to the normal conditions, Q_N , according to Eq. (2), and then converted again to Q under the riser pressure $P = P_{atm}$ and temperature assumed as equal to T_g . After that, the superficial velocity of the air, U_g , was calculated under each test condition from Eq. (1).

$$Q_N = \left(\frac{P_{atm}}{P_N} \right) \left(\frac{T_N}{T_{amb}} \right) Q \quad (2)$$

where Q_N is the flow under normal conditions [NI/h], P_{atm} is the atmospheric pressure [Pa], P_N is the pressure under normal conditions 101325 [Pa], T_{amb} is the ambient temperature [K], T_N is the temperature under normal conditions 273.15 [K], P_m is the pressure and Q is the volumetric flow in (l/h).

Table 1. Points used for the rise and fall fluidization tests.

Test point	U_g [m/s]	G_{ETR} [1]	Test point	U_g [m/s]	G_{ETR} [1]
1	0.015	100	24	0.179	100
2	0.017	100	25	0.199	100
3	0.019	100	26	0.222	100
4	0.021	100	27	0.247	100
5	0.023	100	28	0.275	100
6	0.026	100	29	0.306	100
7	0.029	100	30	0.341	100
8	0.032	100	31	0.380	100
9	0.036	100	32	0.423	100
10	0.040	100	33	0.471	100
11	0.044	100	34	0.525	33.3
12	0.049	100	35	0.584	33.3
13	0.055	100	36	0.651	33.3
14	0.061	100	37	0.725	33.3
15	0.068	100	38	0.807	33.3
16	0.075	100	39	0.899	33.3
17	0.084	100	40	1.002	3.3
18	0.094	100	41	1.116	3.3
19	0.104	100	42	1.242	3.3
20	0.116	100	43	1.384	3.3
21	0.129	100	44	1.541	3.3
22	0.144	100	45	1.716	3.3
23	0.160	100			

During the tests, the electrical charge signal, V_0 , obtained by ETR, the fluctuation signals of the total pressure drop across the bed, Δp_T , acquired by PT2, the gauge pressure, p_m , by PG and Δp_v by PT1, were sampled with an acquisition rate of 1000 samples/s along 60 seconds. These time-series were recorded in the microcomputer MIC.

In the data reduction stage, the time series of each quantity were acquired along 60 seconds with a sampling rate of 1000 samples/s. Half of this time interval was long enough for assuming the system is time-invariant. It because, from each pair of 30-second time-series of electrical charge signals V_0 and pressure fluctuation signals Δp_L , differences of less than 0.5% were observed between the respective means and the standard deviations on all tested conditions. Therefore, only the first 30-second time-series was used for analysis. From this, the mean value of the total pressure, Δp_T , and standard deviation, σ_{pT} and σ_{v_0} , for pressure fluctuation and electrical charge signals under each test condition, was calculated. Besides, to obtain the pressure through the bed of particles, Δp_L , which was used for the application of the method described by Kunii and Levenspiel (1991), the pressure drop value by the distribution plate, Δp_d , was subtracted from the total pressure according to Eq. (3). A mathematical relation of $\Delta p_d \times U_g$ was obtained previously with no mass of solids on the riser.

$$\Delta p_L = \Delta p_T - \Delta p_d \quad (3)$$

First, the method described by Kunii and Levenspiel (1991) was applied to determine the U_{mf} . It was used as a basis of comparison for the other methods used in this work. According to this classical method, the values of Δp_L and U_g obtained through the 45 test points under increasing U_g and of 29 test points under decreasing U_g were used.

From the calculated σ_{pT} values of the pressure fluctuation signals, the method proposed by Puncochar *et al.* (1985) was applied. Then, regarding the method proposed by the authors, the scale of representation of the values of U_g was modified, therefore, by using a logarithmic scale instead of a linear one. For the application of this proposed method, all 45 points with under increasing U_g were used, however, in the graph constructed for the method, only the points referring to the fluidized bed region were represented.

Finally, the same procedure, adopted for the determination of U_{mf} by the modified method of Puncochar *et al.* (1985) with the pressure fluctuation signals, was adopted for the electrical charge signal, σ_{v_0} .

3. RESULTS AND DISCUSSION

Figure 4 shows the characteristic curve of the fluidized bed according to the description of Kunii and Levenspiel (1991). In the vertical axis in log scale, the pressure drop through the bed of particles, Δp_L , in kPa. In the horizontal axis also in log scale, the superficial gas velocity, U_g , in m/s. The blue circles represent the 45 points under increasing U_g and the red circles represent the 29 points under decreasing U_g , according to Tab. 1. From this, the minimum fluidization velocity, U_{mf} , as indicated by the dashed vertical line is equal to 0.178 m/s.

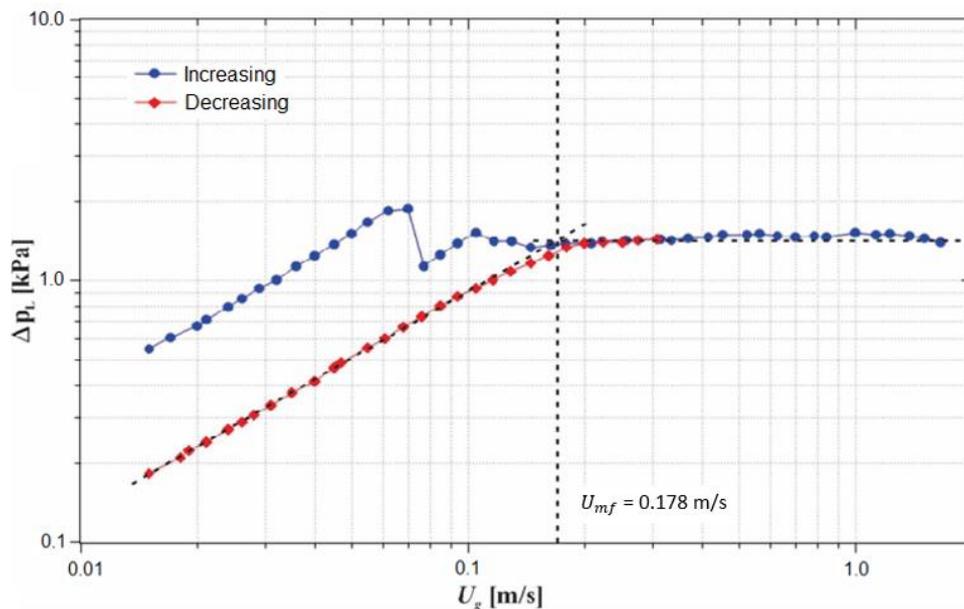


Figure 4. Diagram for determining U_{mf} by the method described by Kunii and Levenspiel (1991).

Figure 5 show diagrams for determining U_{mf} as proposed by Puncochar *et al.* (1985) in (a), and that modified by taking the horizontal axis in log scale in (b), both from signals of total pressure fluctuation. All points were chosen for the application of linear regression, which generates a line that defines the U_{mf} by the interception point with the horizontal axis (U_g) according to the method of Puncochar *et al.* (1985). For the application of the method of Puncochar *et al.* (1985), the authors suggest that the adjusted U_g points are not greater than $2.5U_{mf}$, where U_{mf} can be estimated initially through empirical correlations to determine the upper limit of the U_g range to apply the method (Puncochar *et al.*, 1985). For values greater than $2.5U_{mf}$, there is an increase in the non-linearity between σ_{pL} and U_g (Puncochar *et al.*, 1985). To determine the upper limit of U_g in the application of the method of Puncochar *et al.* (1985), U_{mf} was estimated to be 0.178 m/s, as determined in the method described in Kunii and Levenspiel (1991). From point 29, there was an increase in non-linearity between σ_{pL} and U_g , therefore, for linear regression, points 26, 27, and 28 of Tab. 1 were used. Point 25 was discarded for the linear regression because it presented a non-linearity concerning the other points used in the regression.

From the method of Puncochar *et al.* (1985), it was found that the U_{mf} corresponds to 0.205 m / s, while from the modified method, an U_{mf} equal to 0.205 m/s was obtained. It is observed that the U_{mf} value obtained from the method of Puncochar *et al.* (1985) and the method proposed in this work were identical.

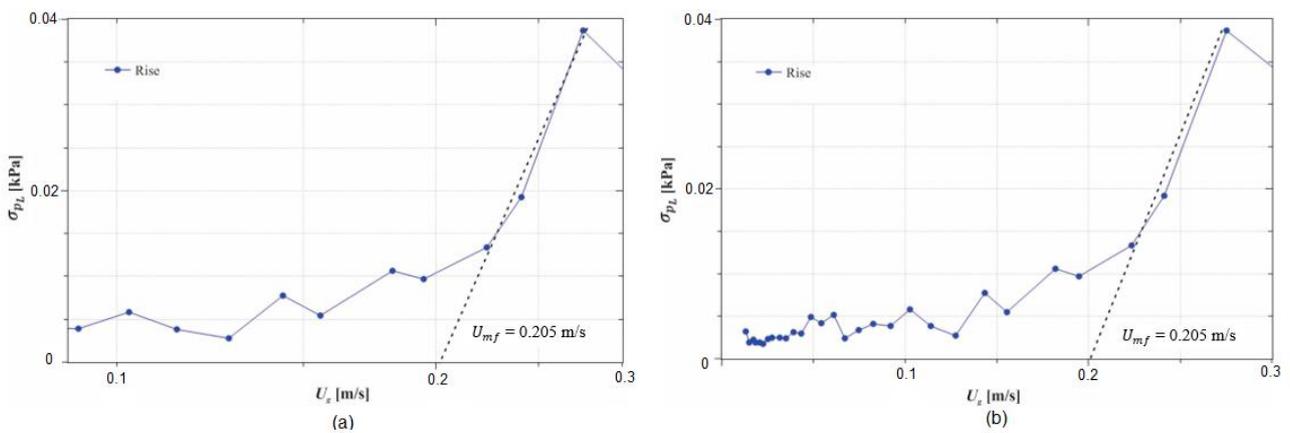


Figure 5. Minimum fluidization velocity using the standard deviation of pressure signals.

Fig. 6 shows the determination of U_{mf} using the modified method of Puncochar *et al.* (1985), applied from a new perspective, that of the signal of electrical charges sensed from the flow. In the graph of Fig. 6, the σ_{v0} axis is represented on a linear scale, while the U_g axis is represented on a log scale. From the interception of the line, obtained through the linear regression of the points where σ_{v0} behaved linearly with U_g , with the horizontal axis of the graph, it was determined that U_{mf} corresponds to 0.175 m/s.

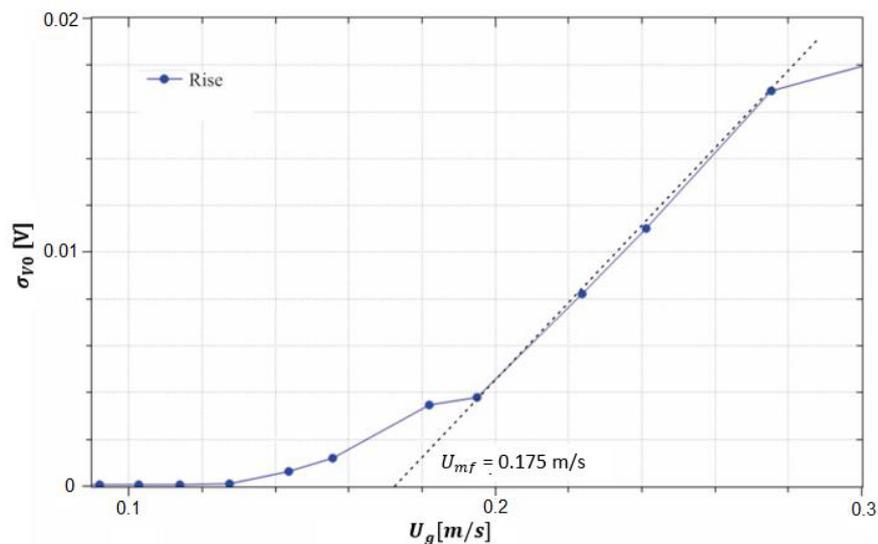


Figure 6. Minimum fluidization velocity using the standard deviations of electrical charge signals.

In addition to the experimental methods presented in Fig. 4, 5 e 6, the minimum fluidization velocity, U_{mf} , for the fluidized bed composed by silica sand was obtained from mathematical modeling. The calculated U_{mf} value was 0.089 m/s. Tab. 2 shows the comparison between the U_{mf} values obtained in this work.

Table 2. Comparison between the U_{mf} values obtained in this research.

Methods	Methodology	U_g
Kunii and Levenspiel (1991) – as described	$\Delta p_L \times U_g$	0.178 m/s
Puncochar <i>et al.</i> (1985) – as described	$\sigma p_L \times U_g$	0.205 m/s
Puncochar <i>et al.</i> (1985) - adapted	$\sigma p_L \times U_g$	0.205 m/s
Puncochar <i>et al.</i> (1985) - adapted	$\sigma_{v0} \times U_g$	0.175 m/s
Theoretical - calculated	Eq. ($Re_{mf} = \frac{D_p U_{mf} \rho_g}{\mu}$)	0.089 m/s

As shown in Tab. 2, the methods based on the analysis of the pressure fluctuation signals by the bed, it was found that the method presented in Kunii and Levenspiel (1991) resulted in an U_{mf} value equal to 0.178 m/s, the method of Puncochar *et al.* (1985) presented an U_{mf} value equal to 0.205 m/s, as well as the method proposed in this work, which is based on Puncochar *et al.* (1985). Regarding the proposed method, which is also based on Puncochar *et al.* (1985), however, uses the signal of electrical charges generated during the flow, an U_{mf} equal to 0.175 m/s was obtained. The U_{mf} obtained through the electrical charge signal is 1.69% lower than the U_{mf} obtained through the pressure fluctuation signal, both obtained through the modified method of Puncochar *et al.* (1985), where U_g is presented on a logarithmic scale. If compared with the U_{mf} value obtained in mathematical modeling, 0.089 m/s, the method that obtained the closest result was the one based on the analysis of the electrical charge signals of the ring-shaped sensor, however, it is still about 94.4% higher.

4. CONCLUSIONS

In this work, a non-intrusive ring-shaped electrical charge sensor was tested to determine the minimum fluidization velocity of a silica sand fluidized bed under cold operation. The parameters, such as the signals of differential pressure and electrical charges, airflow rate, and airflow temperature, were acquired and saved through a data acquisition program developed in the LabView software.

Regarding the determination of the minimum fluidization velocity (U_{mf}): the minimum fluidization velocity of the fluidized bed was determined using the signals of pressure fluctuation and electric charges, using the methods used by Puncochar *et al.* (1985) and Kunii and Levenspiel (1991). The U_{mf} obtained by the pressure signals was 0.178 m/s, by the method used by Kunii and Levenspiel (1991) and 0.205 m/s by the method used by Puncochar *et al.* (1985). The U_{mf} obtained by the electrical charges signals from the ring-shaped sensor was 0.175 m/s, the closest value to the calculated U_{mf} .

Finally, it is highlighted that the proposal for a method adapted from Puncochar *et al.* (1985), applied on electrical charge signals, is feasible for determining the minimum fluidization velocity of a cold fluidized bed using a ring-shaped electrical charge sensor.

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