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PREDICTION OF OPERATING PARAMETERS OF A LOOP-SEAL VALVE COUPLED TO A BENCH-SCALE CIRCULATING FLUIDIZED BED SYSTEM

Adinaldo Valaszek
Jhon Jairo Ramirez-Behainne
Federal University of Technology - Paraná – UTFPR, Monteiro Lobato Ave., km 04. CEP: 84016-210, Ponta Grossa/Brazil.
adinaldovalaszek@gmail.com, jhon@utfpr.edu.br

Abstract. *This paper studies the effect produced on the main operating parameters of a loop-seal valve when several experimental conditions are tested in a cold flow bench-scale circulating fluidized bed (CFB) system. Based on previous researches of literature, a semi-empirical mathematical model was proposed in order to determine how the fluidizing gas velocity and the total inventory of 256 μm mean diameter quartz sand particles affect the pressure drop in main components of the system, the solids circulation rate through the loop-seal and the external aeration rate required for stable operation. The simulations showed that varying the fluidizing gas velocity from 4.0 to 5.5 m/s and the total solids inventory from 3.5 to 5.5 kg, the pressure drop through the CFB system follows the solids mass distribution obtained in the riser and the two chambers of the loop-seal valve. By using the sharp crested theory was verified that increasing the external solids circulation flux, the height of solids above the barrier of the recycling chamber also growths. In addition, it was found that the aeration mass rate in the supply chamber of the loop-seal is more critical than in the recycling chamber. Results obtained from the model were in agreement with published data.*

Keywords: *loop-seal, circulating fluidized bed, gas-solid flow.*

1. INTRODUCTION

Circulating fluidized beds (CFBs) are systems used in combustion, gasification, catalytic reactions and many others gas-solid contacting processes. In applications involving thermochemical operations, CFBs have shown advantages in energy conversion efficiency and environmental impact due to the high heat and mass transfer rates they promote.

Normally, a CFB is composed by a fluidization loop including a riser, cyclone, standpipe and a valve that controls the particle circulation by using mechanical or non-mechanical parts. In particular, the loop-seal valve is a non-mechanical control valve composed by a supply chamber, recycle chamber, over flow pipe, opening between the two chambers, plenum and gas distributor. The main sections of the CFB loop and details of its loop-seal valve are illustrated in Fig. 2.

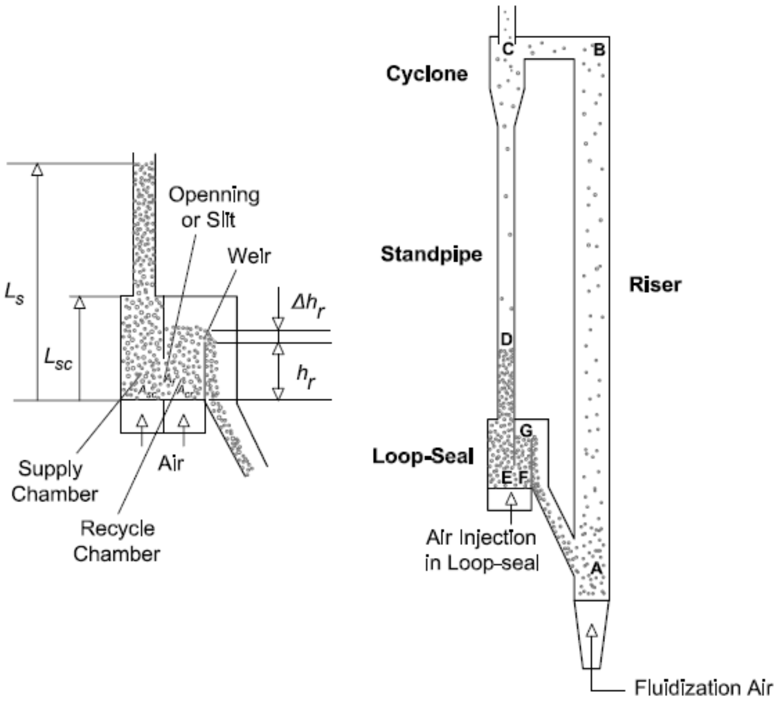

Figure 1 – CFB system with loop-seal details. Adapted from Basu and Cheng (2000).

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The loop-seal valve is a critical component of CFB units and its failure causes the fluidization systems to cease operation as solids build-up in the standpipe attaining the cyclone or when the fluidizing gas finds a path for crossing through the valve toward cyclone due to insufficient seal effect at very low solids inventory or total mass of solids in bed (Basu, 2006).

Previous works have explored the basic principle of loop-seal operation and the effect of some parameters of the fast fluidized bed regime upon the gas-solid hydrodynamics in CFB systems. Kim and Kim (2002) studied the effects of particle size and density on solids recycle characteristics of loop-seal. Experiences with five different particles indicated that as the particle size is increased, aeration requirement in the loop-seal also increases. In addition, it was found that the aeration rate, particle size, and density affect the pressure balance around the CFB. According the authors, as particle size is increased, solid holdup in the riser decreases at a given external solids recycle rate and gas velocity, and the pressure drop in the weir section of loop-seal increase with larger and denser particles. In the vertical aeration section, results showed the pressure drop increases with decreasing particle size and increasing particle density.

Basu and Butler (2009) showed that the horizontal length localized between the feeding and recycle chambers of a loop-seal affects the aeration requirement. They verified that the minimum aeration for the onset of solids flow increases with increase in this length, as well as, the pressure drop per unit length across the passage. Li, *et al.* (2011) showed that the loop seal operation status in circulating fluidized beds exhibits three different types of flow characteristics: non-operation, operation with solids height in the standpipe, and operation without solids in the standpipe. According the authors, the operation conditions will be forced by the pressure balance in the CFB loop. More recently, mathematical model have been published aiming to predict the relationship between operation parameters and hydrodynamics of the gas-flow in a loop-seal valve (Wang, *et al.,* 2013).

Although in wide use in thousands of CFB units, only a limited amount of research is published on the operation of these devices. A lack of proper understanding of the operation of the loop-seal prevents rational scale up, design and can lead to problems with the operation of the loop-seal. Taking into account such aspect the present work analyzes, based on the sharp crested theory, the effect on aeration, solids recycle rate and pressure drop in a loop-seal valve coupled to a bench-scale CFB unit as the total solids inventory and the fluidizing gas velocity change of levels at atmospheric temperature and pressure conditions.

2. MATHEMATICAL MODEL

The mathematical model used in this study was adapted from the semi-empirical model previously proposed by Rodrigues and Beltrane (2011), in which a calculation procedure was implemented for sizing a bench-scale CFB loop operated with a L-type valve based on correlations found in literature.

According Basu and Cheng (2000), for stable operation of the fluidized loop the static pressure balance in the gas-solid system must be expressed in terms of the pressure through sections of the CFB loop, as described by Eq. (1):

$$(P_A - P_B) + (P_B - P_C) + (P_C - P_D) + (P_D - P_E) + (P_E - P_F) + (P_F - P_G) + (P_G - P_A) = 0 \quad (1)$$

Point D in Fig. 1 is the upper surface of the solids column in the standpipe. As suggested by the authors, the pressure drop along paths (B-C) and (G-A) were no considered. Thus, according to the pressure balance established in the loop, the pressure drop in the supply chamber and standpipe (ΔP_{E-D}) should be equal to the sum of the pressure drops in the riser (ΔP_{A-B}), the cyclone (ΔP_{C-D}), the opening between the chambers (ΔP_{E-F}) and the chamber recycling (ΔP_{F-G}), according Eq. (2):

$$\Delta P_{E-D} = \Delta P_{A-B} + \Delta P_{C-D} + \Delta P_{E-F} + \Delta P_{F-G} \quad (2)$$

For the riser, the pressure drop above the solids recycle point (ΔP_{A-B}) can be calculated through the Eq. (3):

$$\Delta P_{A-B} = \Delta P_r - g\,(1 - \varepsilon_a)\rho_s H_{sr} \quad (3)$$

where ΔPr is the pressure variation for the entire length of the riser; ε_a, the average porosity in the bottom of the riser; ρ_s, the density of the solid particles; H_{sr}, the height of the solids recycle point, and g, the gravitational acceleration.

Considering the cyclone region, the total pressure variation (ΔP_{C-D}) is established by Eq. (4), according Basu (2006):

$$\Delta P_{C-D} = \Delta P_e + \Delta P_f \quad (4)$$

where ΔP_e and ΔP_f are the pressure variation in the gas exit duct and in the separation compartment, respectively. These terms are determined through Eq. (5) and (6):

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$$\Delta P_f = f_w \frac{A_{sit}}{0.9Q} \frac{\rho_g}{2} (u_a u_i)^{\frac{3}{2}} \tag{5}$$

$$\Delta P_e = \left[2 + 3 \left(\frac{u_i}{v_i}\right)^{\left(\frac{4}{3}\right)} + \left(\frac{u_i}{v_i}\right)^2\right] \frac{\rho_g}{2} {v_i}^2 \tag{6}$$

where f_w is the friction coefficient of the gas-solid flow; A_{sit} is the total internal area of the cyclone; Q is the gas flow entering the cyclone; u_a is the tangential velocity at the outer radius of the cyclone and v_i is the mean gas velocity in the exit tube. Both equations are dependent of the gas density (ρ_g) and tangential velocity in the internal diameter of the gas exit duct (u_i).

The sections referents the loop-seal valve will be presented in detail below.

2.1 Pressure Drop in the Supply Chamber

In this section, the downward flow of the particles takes place in moving bed condition, where the slip velocity or relative velocity between the gas and solid phases determines the pressure drop (Basu and Butler, 2009). Thus, the pressure drop in the supply chamber and the standpipe ($\Delta P_{E\text{-}D}$) can be obtained by the modified Ergun equation, which is shown in Eq. (7):

$$\frac{\Delta P_{E-D}}{L_s} = 150\left(\frac{(1-\varepsilon_s)^2}{\varepsilon_s^3}\right)\left(\frac{\mu \Delta u}{(\emptyset_s d_s)^2}\right) + 1.75\left(\frac{1-\varepsilon_s}{\varepsilon_s^3}\right)\left(\frac{\rho_g (\Delta u)^2}{\emptyset_s d_s}\right) \tag{7}$$

In Eq. (7), Δu is the slip velocity, which is determined by the sum of the gas velocity (u_{sg}) and the solids velocity (u_s), according Eq. (8):

$$\Delta u = u_{sg} + u_s = \frac{u_0}{\varepsilon_s} + u_s \tag{8}$$

The u_s value is calculated by Eq. (9), which involves the solids circulation rate in the standpipe (G_{ssp}), the solids density (ρ_s) and the bed porosity in the column (ε_s):

$$u_s = \frac{G_{ssp}}{\rho_s(1-\varepsilon_s)} \tag{9}$$

The G_{ssp} value is determined by Eq. (10) in terms of the cross section diameter of the column (M) and the rate of solids discharged into standpipe (m_{ssp}), which is known from the riser hydrodynamic model and the cyclone efficiency:

$$G_{ssp} = \dot{m}_{ssp}\left(\frac{4}{\pi M^2}\right) \tag{10}$$

According to Basu (2006), the minimum fluidization gas velocity of the particles in the column must be equal to the slip velocity. Thus, the minimum fluidization gas velocity in the loop-seal valve (u_{mf}) was calculated by Eq. (11):

$$u_{mf} = \frac{\mu}{d_s \rho_g}\left[(27.2^2 + 0.0408\, A_{rL})^{0.5} - 27.2\right] \tag{11}$$

where the Arquimedes number (A_{rL}) is determined by Eq. (12):

$$A_{rL} = \frac{\rho_g(\rho_s - \rho_g) g d_s^3}{\mu^2} \tag{12}$$

The gas velocity in the standpipe (u_0) is known by solving Eqs. (7) to (12). u_0 is positive in the case of upward flow, or negative for a downward flow. From the u_0 value, the air flow needed in the standpipe and the supply chamber (Q_{SP}), can be calculated by Eq. (13):

$$Q_{SP} = u_0 A_{sp} \tag{13}$$

Finally, from Eqs. (14) and (15) the solids inventory in the standpipe (I_{ssp}) and the supply chamber (I_{sca}) were determined, respectively:

$$I_{ssp} = (1 - \varepsilon_s)\rho_s A_{sp}(L_s - L_{sc}) \tag{14}$$

$$I_{sca} = (1 - \varepsilon_s)\ \rho_s\ A_{sc}L_{sc} \tag{15}$$

where, A_{sp} represents the cross-sectional area of the standpipe; A_{sc}, the cross-sectional area of the supply chamber; L_S, the height of accumulated solids in the standpipe, and L_{sc}, the height of the supply chamber.

2.2 Pressure Drop across the Slit

To calculate the pressure drop through the horizontal passage in the loop-seal ($\Delta P_{E\text{-}F}$), the expression proposed by Kuramoto et al. (1986) was used:

$$\Delta P_{E-F} = 0.66\left(\frac{A_f}{A_{sc}}\right)^{-1.2} G_{sf} \tag{16}$$

where A_F is the area of the opening between the chambers; A_{sc}, the cross-sectional area of the supply chamber and G_{sf}, the solids circulation rate through the slit.

Basu and Butler (2009) indicate that the slip velocity in the horizontal section of a solid recycle valve is slightly higher than the minimum fluidization gas velocity of solids. For this work, a value equal to 1.1 u_{mf} was considered for the slip velocity through the slit. Taking into account the horizontal velocity value (U_H), the flow rate of air passing the slit of the loop-seal valve (Q_H) was calculated according Eq. (17):

$$Q_H = U_H A_f \tag{17}$$

2.3 Pressure Drop in the Recycle Chamber

In recycle chamber the solids are fluidized by air entering at the bottom of this section. If properly designed, the chamber must allow the bed level exceeding the height of the weir, as illustrated in Fig. 1. According to Basu and Cheng (2000), the pressure drop in the recycling chamber ($\Delta P_{F\text{-}G}$) can be determined by Eq. (18):

$$\Delta P_{F-G} = (1 - \varepsilon_r)(h_r + \Delta h_r)\rho_s g \tag{18}$$

The height of suspended solids above the weir (Δh_r) is found by using the sharp-crested theory (White, 1999). According to this theory, the volumetric flow of the fluidized solids (Q_s) can be calculated by Eq. (19):

$$Q_s = C_d\ g^{0.5}\Delta {h_r}^{1.5}\ W \tag{19}$$

where C_d is the discharge coefficient; W, the weir width, and g, the acceleration of gravity. Basu and Cheng (2000) show that the porosity in the recycling chamber (ε_r) can be known by the expression:

$$\varepsilon_r = \frac{u_r + 1}{u_r + 2} \tag{20}$$

In Eq. (20), the velocity of the gas in the recycle chamber (u_r) must be enough to carry the solids coming from the supply chamber and promote these solids to overflow the weir. According Basu (2006), the slip velocity in this section is calculated by:

$$\Delta u_{cr} = u_{mf} + 0.07\ (\ g\ M)^2 \tag{21}$$

Thus, the air flow passing through the recycling chamber (Q_{CR}) is obtained by Eq. (22):

$$Q_{CR} = u_r A_{cr} \tag{22}$$

On the other hand, the solids inventory needed in the recycle chamber is given by Eq. (23), according Basu and Cheng (2000):

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$$I_{scr} = (1 - \varepsilon_r)\rho_s A_{cr}(h_r + \Delta h_r) \tag{23}$$

Finally, the total solids inventory (I_{ST}) in the CFB loop was determined by adding the solids inventory found in each section:

$$I_{sT} = I_{sr} + I_{ssp} + I_{sca} + I_{scr} \tag{24}$$

where, I_{sr} is the solids inventory of riser.

2.4 Total Aeration Required in the Loop-Seal Valve

The aeration required in each chamber of the loop-seal valve was determined by mass balance. Thus, the aeration needed in the supply chamber (Q_1), the recycling chamber (Q_2) and the total aeration in loop-seal valve (Q_T) was obtained by the Eqs. (25) to (27), respectively:

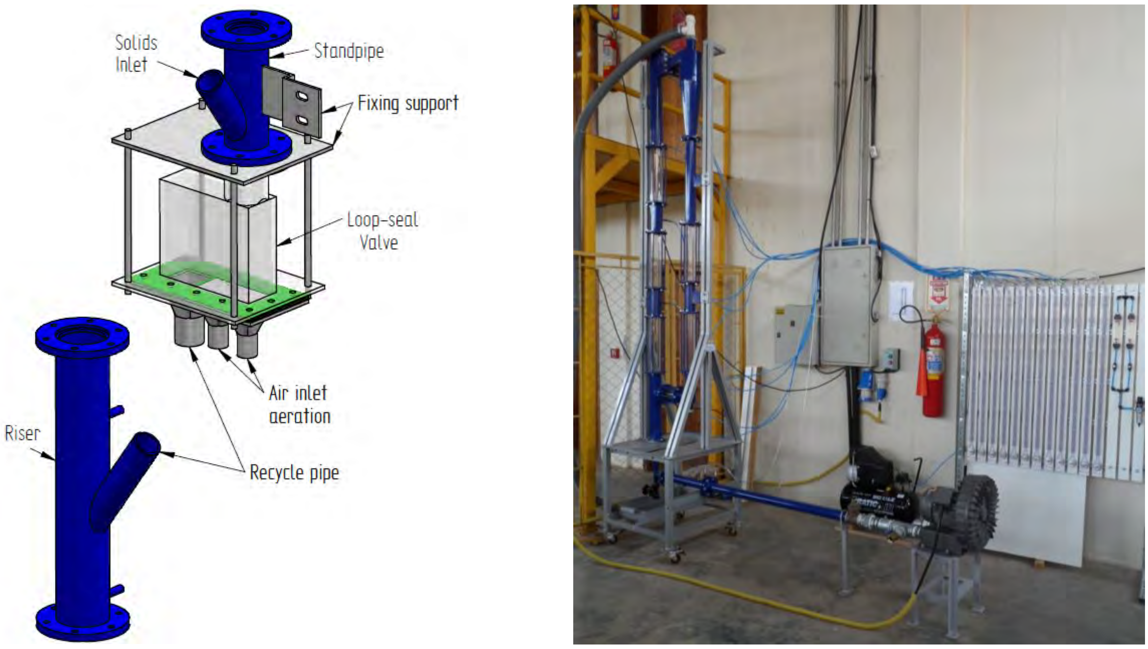
$$Q_1 = Q_H + Q_{SP} \tag{25}$$

$$Q_2 = Q_{CR} - Q_H \tag{26}$$

$$Q_T = (Q_1 + Q_2) \tag{27}$$

2.5 L-valve Design

In the adapted model, fundamental equations describing the operation of a loop-seal valve substituted the L-valve equations in order to allow the simulation of the CFB system connected to the new solid recycle device. Figure 1(a) illustrates a three-dimensional drawing of the loop-seal valve and other components coupled to the Cold Fast Fluidization Unit – CFFU (Fig. 1b) developed by Valaszek and Marin (2013), and localized in the Thermochemical Processes Laboratory of the Mechanical Engineering Department at UTFPR/Ponta Grossa.



(a) (b)

Figure 1– (a) Loop-seal (a); (b) CFFU used in experimental tests.

2.6 Caracterization of the Bed Particles

The mathematical model described above used information associated to the characteristics of the bed particles, such as mean particle diameter, sphericity and density of the solids. The characterization was performed for quartz sand particles. Sand with diameter between 200 and 300 µm are often utilized by researchers in experimental units of similar

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scale considered in this work for obtaining an appropriated fluidization (Howard, 1989). Particles passing sieves with mesh 50 (300µm) and retained in mesh 70 (212µm) were chosen. So, a mean particle diameter equal to 256 µm was considered in simulations.

The apparent density of quartz sand particles were measured by picnometry with distilled water. The average value of three tests was 2,522 kg/m^3, with a standard deviation of 31.7 kg/m^3.

The sphericity of the particles was found using the method proposed by Massarani and Peçanha, who are cited for Cortez *et al*. (2008). By using an optical microscope Olympus, model BX60, one hundred measurements were performed, obtaining the average sphericity of 0.69 with a standard deviation of 0.086.

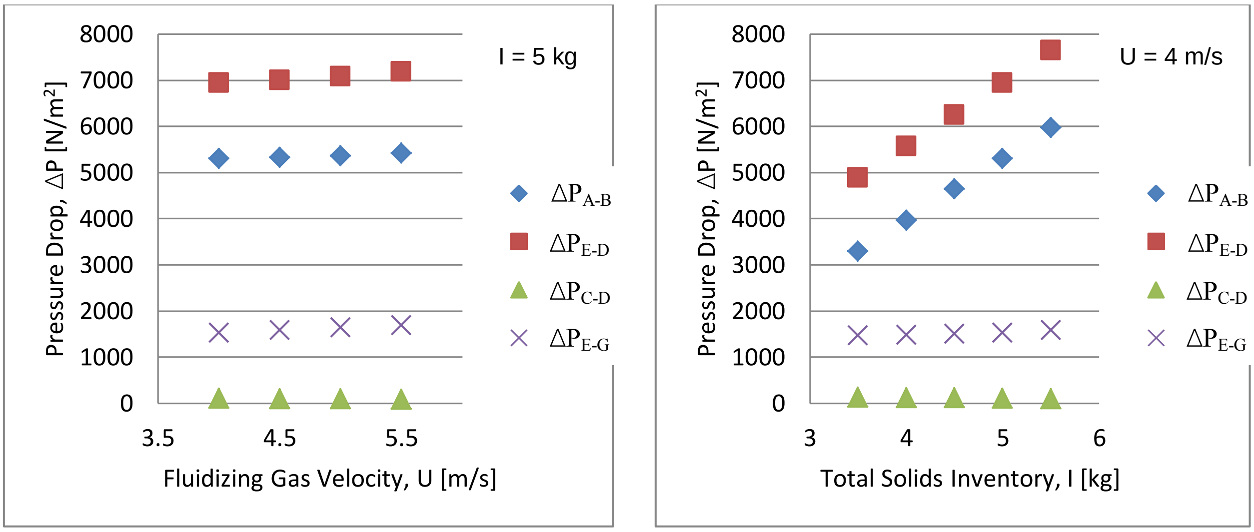
3. RESULTS AND DISCUSSIONS

Simulations using fluidizing gas velocities from 4.0 to 5.5 m/s and solids inventory between 3.5 and 5.5 kg were carried out in order to predict the operating parameters of the loop-seal valve coupled to the CFB system. The main dimensions of the CFB loop considered in simulations were those shown in Table 2. Also, the average bed porosity in the bottom of the riser (ε_a) was fixed in 0.9 (Basu, 2006). The mathematical model equations were solved using the ESS® software.

Table 2–Main dimensions of the FBC system imposed in the mathematical model.

Geometric parameter	Value (m)
Inner diameter of the riser column (D_r)	0.078
Height from the riser base to the inlet point of the cyclone (H)	2.7
Inner diameter of cyclone (D_c)	0.145
Inner diameter of standpipe (M)	0.059
Height of the supply chamber (L_{sc})	0.171
Hydraulic diameter for the supply chamber of the loop-seal (D_h)	0.059
Hydraulic diameter for slit of the loop-seal (D_f)	0.059
Hydraulic diameter of the recycle chamber in the loop-seal (D_{cr})	0.059
Width of the weir recycle chamber in the loop-seal (W_L)	0.059
Thickness of the weir in the loop-seal (e_t)	0.003

The pressure balance in the CFB loop can be affected by several factors. In this work, we analyze specifically the pressure drop in the fluidized bed due to the variation of the fluidizing gas velocity and the solids inventory. The effect of these parameters is shown in Fig. 3(a) and 3(b), respectively.



(a) (b)

Figure 3 - Pressure drop in the fluidization loop. (a) Variation with the fluidizing gas velocity; (b) Variation with the total solids inventory.

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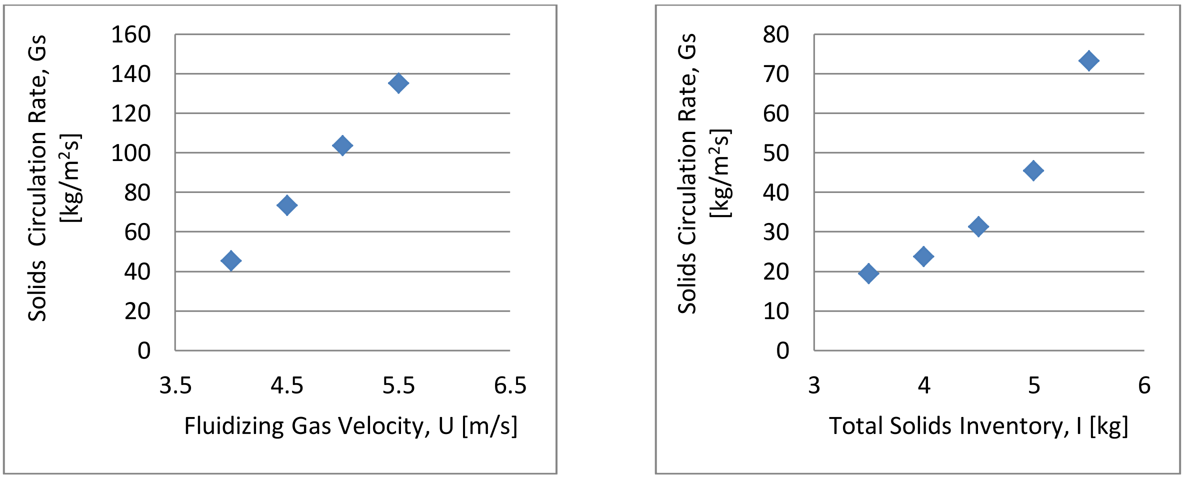
Results of pressure drops in components of the CFB loop showed that the standpipe and the riser are the more sensitive sections, mainly when the solids inventory varies. This occurred because the mean bed porosity of the bed reduced by increasing the bed inventory.

On the other hand, the pressure drop in all components indicated small variations regarding the fluidizing gas velocity in the range tested. In the riser, the pressure drop level was practically maintained due that the reduction promoted by the more bed porosity per length unit was balanced by the particle-wall friction, which is enhanced in this situation due to the higher solids circulation rate.

In particular, the pressure drop in the loop-seal valve slightly increases with increasing both the fluidizing gas velocity and the solids inventory. The pressure drop in this component is at intermediate level, between the pressure drop obtained in the cyclone and the standpipe. These results showed a similar behavior when compared with those presented by Yang and Yang *et al*. (2009).

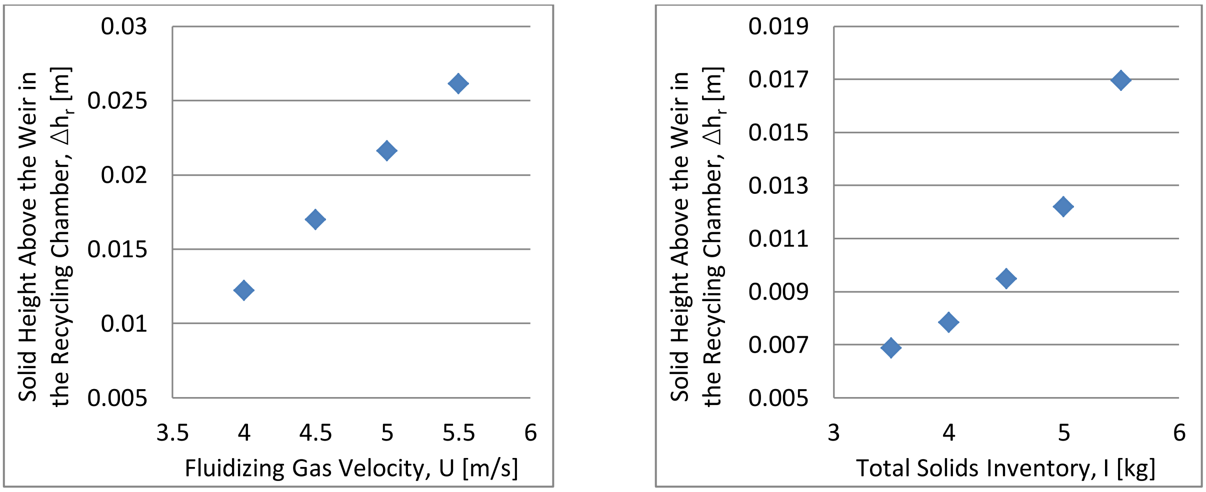
Regarding the recirculation rate of solids, Fig.4(a) and 4(b) show that increasing the fluidizing gas velocity and the total solid inventory promotes a higher solid circulation rate (G_s). In this case, G_s growth linearly and exponentially with the fluidizing gas velocity and the total solids inventory, respectively. This G_s behavior had been evidenced by Basu (2006).



(a) (b)

Figure 4 – Solids circulation rate behavior, Gs:(a) Variation of the fluidizing velocity;
(b) Variation of the solids inventory.

The effects of the fluidizing gas velocity and the total solids inventory on the recycling chamber weir (Δh_r) are illustrated in Fig. 5(a) and 5(b), respectively.

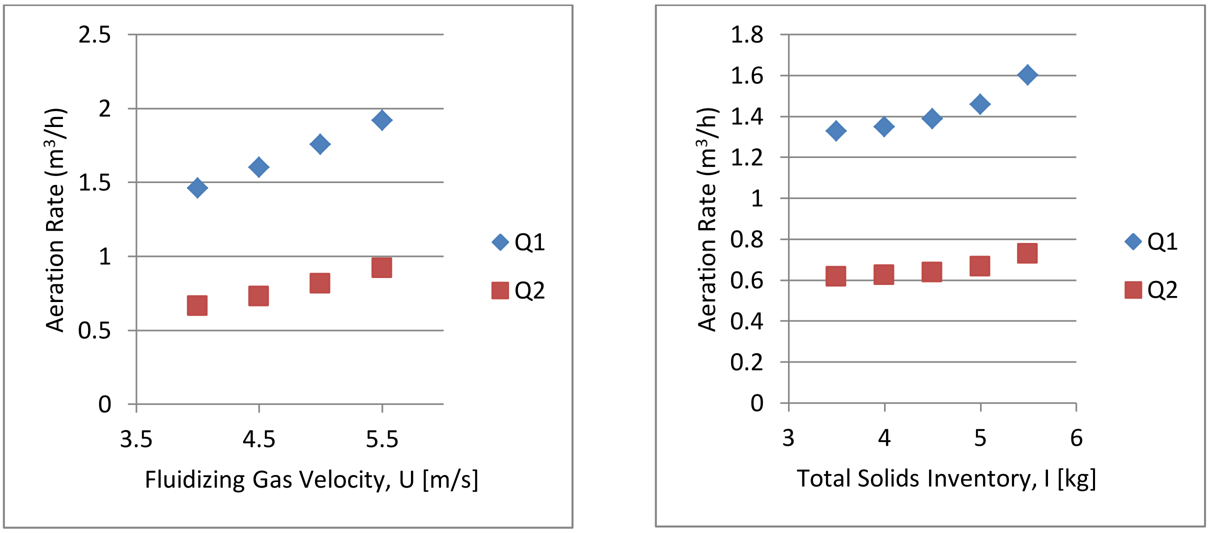


(a) (b)

Figure 5 – Solid height above the weir in the recycle chamber, Δh_r:(a) with the varying the fluidizing velocity; (b) with the variation of the inventory of solids.

Results from Fig. 5 show that the height of solids above of the weir recycle chamber increased with both the fluidizing gas velocity and the total solids inventory, which is consistent with the real phenomenon. As noted in Fig. 5, the total solids inventory caused a higher effect in comparison with that produced by the fluidizing gas velocity.

There was also variation in the aeration rate for the supply chamber (Q_1) and the recycling chamber (Q_2) with changes in the fluidizing gas velocity and the total solids inventory, as can be seen in Fig. 6(a) and 6(b), respectively.



(a) (b)

Figure 6 – Aeration rate in the supply chamber (Q_1) and in the recycle chamber (Q_2). (a) Variation of the fluidizing gas velocity; (b) Variation of the total solids inventory.

It can be noticed that the aeration rate values in the supply chamber are higher than those presented in the recycling chamber, in order to provide a slip velocity or relative velocity between gas and solids equal to the minimum fluidization gas velocity. The Q_1 aeration still needs to provide the conditions for that the solids get to pass through the slit and return to the chamber recycling. In this chamber, Q_2 aeration should be sufficient to transport the solids above the dam, thereby regulating the solids flow circulation in the loop.

4. CONCLUSIONS

A semi-empirical mathematical model was proposed for assessing the operation of a loop-seal valve coupled to a bench-scale circulating fluidized bed unit. Several total solids inventory and fluidizing gas velocities conditions were simulated in order to determine the pressure drop in the riser, cyclone, standpipe and recycle valve of the CFB loop, as well as, the solids recycle rate and aeration rate needed in the loop-seal. The simulations carried out shown that the pressure drop in several components increases mainly with the total solids inventory, and slightly with the fluidizing gas velocity. The external circulation rate of solids and the height of particles above the weir recycle chamber showed a linear and exponential behavior with increasing the fluidizing gas velocity and the total inventory of solids, respectively. The aeration rate in both the supply chamber and recycle chamber is an essential parameter for operating the loop-seal valve in stable condition. Results indicated that the aeration mass rate required in the supply chamber of the loop-seal is approximately twice that needed in the recycling chamber.

The comparison of results with literature data suggest that the model provides a good approximation of the phenomena occurring in the main components of a bench-scale CFB system. A better understanding of how these components work help for a better characterization of the gas-solid flow in circulating fluidized bed systems built on small scale, aiming at the future design of pilot circulating fluidized furnaces for more efficient energy conversion and minor pollution impact during burning solid fuels such as coal and several Brazilian biomass.

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