Mathematical Modeling and Application of a Continuous Alumina Feeding to Potroom

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Abstract

Mathematical models are used to predict the mass flow rate and the full alumina fluidization velocity of enriched alumina and other powders used in aluminum smelters. For the validation of the models, round non-conventional air slides were manufactured with possibility of multiple outlets. The air fluidized conveyor is made of a low weight, insulating, heat-resistant material, easy to install, maintained without the need to stop the aluminum production of the pot. It also operates at very low cost compared to the conventional metallic air slides. Its air consumption is low and the system can be lifted by the hands for the installation on the top of the pot without the need of welding or disassembling any part of the reduction cell. The fluidized pipeline can be installed even in the upward direction, and it does not interfere with pot operations. The paper also focuses on the scale up of the fluidized pipeline from laboratory studies to industrial application in an aluminum smelter. The paper shows the challenges to optimize the prototype fluidized pipeline and the final adjustments to be used in the continuous pot feeding in aluminum smelter potrooms.

Keywords: Fluidized pipeline, aluminum reduction pot, minimum and full alumina fluidization velocity, alumina mass flow rate.

1. Introduction

Old aluminum smelters feed their electrolytic cells with overhead cranes as can be seen in Figure 1. This is a difficult task to be performed by operators and causes spillage of alumina to the pot room workplace. This problem is currently being solved in Albras by the development of a special multi-outlets nonmetallic fluidized pipeline [1] – see Figure 2.

(a) (b)

Figure 1. a) Overhead crane being fed with fluorinated alumina from a day bin by a standard air slide, b) Overhead crane feeding pot silos with fluorinated alumina.

Figure 2. Multi-outlets nonmetallic fluidized pipeline – during erection time.

The fundamentals of powder transport are illustrated in Figure 3, from the fluidized bed to pneumatic transport regime.

Firstly, the alumina used as raw materials in the primary aluminum process is characterized using sieve analyses (granulometry size distribution). Then, bulk and real densities are determined in the laboratory analyses. Based on these physical properties, powders can be classified in four types using the Geldart's diagram, illustrated in Figure 4 [2]. Most powders used in aluminum smelters belong to groups A and B.

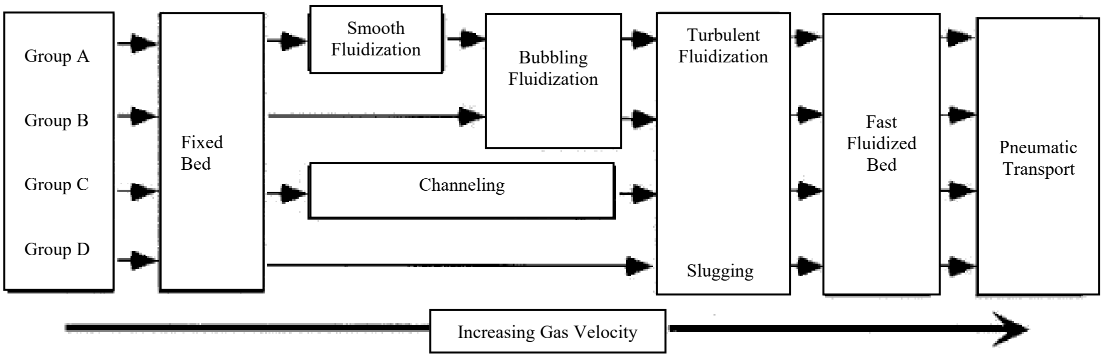

Figure 3. Flow regime map for various powders.

Figure 4 summarizes the fluidized bed hydrodynamics related with powders classified according to Geldart's criteria. Once the velocities associated with each mode of operation are determined, the pressure drop of the regime is calculated so that the gas-solid flow is predicted using suitable modeling and software to optimize the industrial installation.

An equation to predict the mass solid flow rate of the air-fluidized conveyor was developed as a result of a doctorate thesis [1]. Said equation has design purpose and was used in the design of a continuous alumina feeding system for aluminum reduction cells.

Fluidization

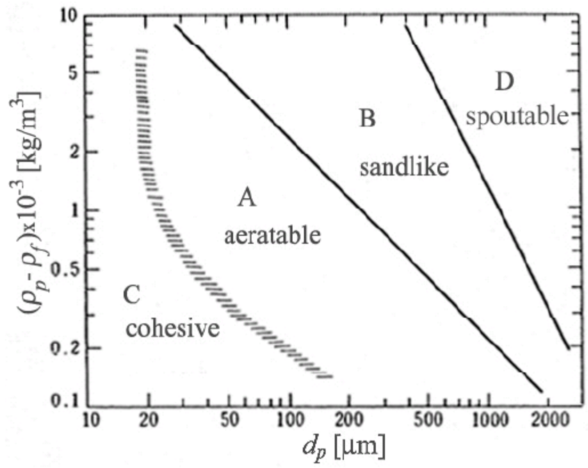

Figure 4. Powder classification diagram for fluidization by air [3].

2. Fundamentals of Powder Fluidization

Fluidization occurs when a fluid (liquid or gas) ascend trough a bed of particles, providing these particles with a minimum fluidization velocity V_{mf}, sufficient to suspend them, but not carrying them with the ascending flow. At this time, the powder behaves like a liquid at boiling point – hence the term "fluidization". Figures 5 and 6 provide a good understanding of the minimum fluidization velocity concept.

2.1. Minimum Fluidization Velocity Calculation

Figure 3 illustrates the beginning (fluidized beds) and the ending (pneumatic transport) of the flow regime map. The minimum fluidization velocity for the fluorinated alumina was calculated using Equation 4, while is experimental figure was obtained using a permeameter.

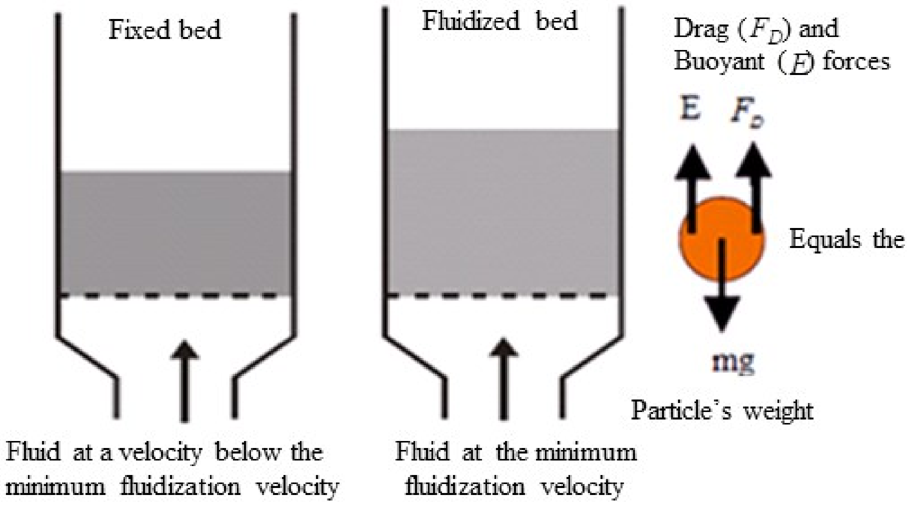

Figure 5. Fixed and fluidized bed of particles at a minimum fluidization velocity - adapted from Kunii and Levenspiel [6].

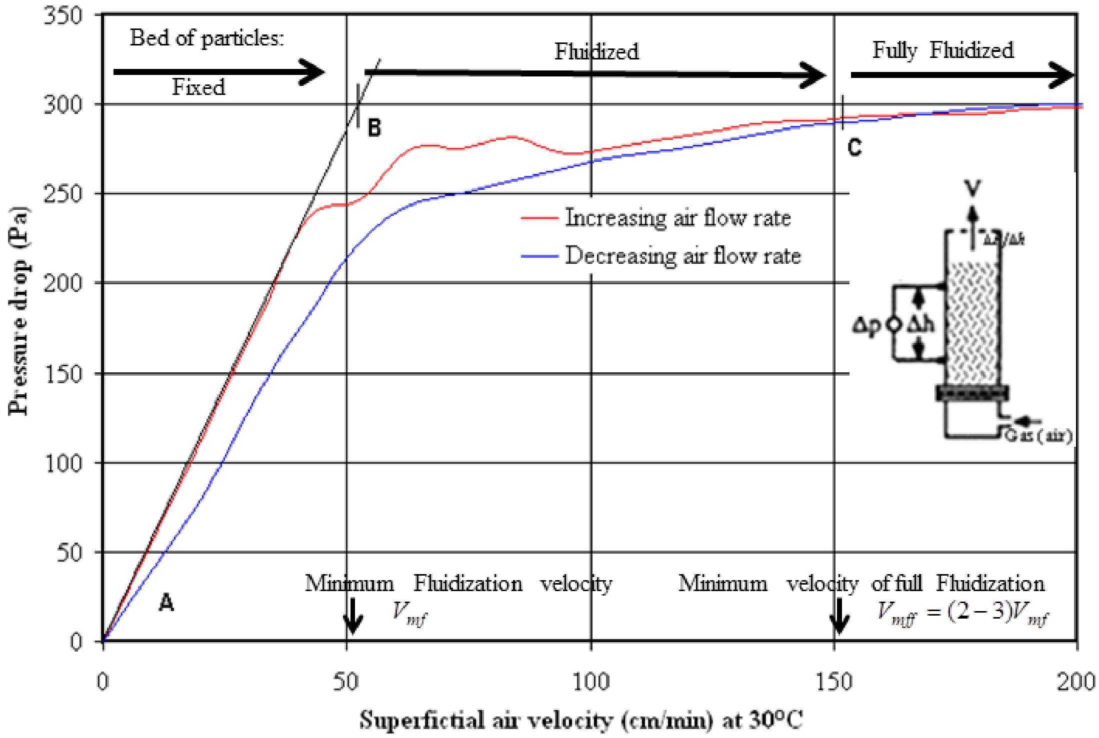

Figure 6. Pressure drop through a bed of particles versus superficial air velocity [4].

For incipient fluidization (that is, when the weight of particles equals the drag force), a reasonable first approximation is to consider that the porosity at the minimum fluidization velocity ε_{mf} equals the porosity ε of the fixed bed, calculated by Equation 1.

$$\varepsilon = 1 - \frac{\rho_{bnv}}{\rho_s} \quad (1)$$

$$\rho_{bnv} = \frac{M_s}{V_{total}} \quad (2)$$

$$\frac{1-\varepsilon}{\phi_s} = 0.255.Log(d_p) + 1.85 \quad (3)$$

where:

- ε Porosity or volume occupied by the solid in a bed of solids of a permeameter, -
- ε_{mf} Porosity of the fluidized bed of solids of the permeameter, -
- ρ_{bnv} Non-vibrated bulk density, kg/m^3
- M_s Mass of non-vibrated particles of volume V_{total} in a sample previously weighted, kg
- V_{total} Total volume of particles and voids in the sample previously weighted, m^3
- ϕ_s Particle sphericity. -

Equation 4 is used for the prediction of the minimum fluidization velocity for fluorinated alumina, while the data required to compute said velocity is obtained from a doctorate thesis by Vasconcelos [1]. Archimedes' Number is calculated by Equation 5.

$$V_{mf} = 0.21(A_r)^{0.25}\left(\frac{\phi_s}{1.05\varepsilon}\right)^{0.7}(d_p g)^{0.5} \quad (4)$$

$$A_r = \frac{d_p^3(\rho_s - \rho_g)\rho_g g}{\mu_g} \tag{5}$$

where:

d_p Solid mean diameter, m

g Acceleration due to gravity, m/s^2

ρ_s Real solid density, kg/m^3

ρ_g Gas density, kg/m^3

μ_g Gas viscosity, $Pa.s$

The experimental value of both V_{mf} and minimum velocity of full fluidization V_{mff} are obtained using a permeameter. Both, the gas superficial velocity and the pressure drop through the bed of particles are measured.

3. Air Fluidized Conveyor (Non-Metallic Round Air Slide)

A non-conventional air slide, called air fluidized conveyor, was developed with a low weight, insulating, heat resistant material. It was designed to be easy to install, maintain and to operate at a very low cost compared with conventional metallic air slides. The left-hand side of Figure 7 shows a conventional air slide with rectangular shape, with one inlet and one outlet. The new round air fluidized conveyor with the possibility having multiples outlets is shown in both central and right-hand images.

Figure 7. The Albras aluminum smelter air fluidized conveyor (center and right) and a conventional air slide (left) [6].

3.1. Predicted and Experimental Behavior of the Air Fluidized Conveyor

Two air-fluidized conveyors – designed according to Equation 6 – were developed as result of a doctorate thesis [1]. The predicted results for the conveyor with an internal diameter of 76.2 mm and 1.5 m in length shown in Figure 8 are summarized in Table 1 while its experimental values, in Table 2.

$$\dot{G} = \left[\frac{(150.(1-\varepsilon_f)^3.\mu_g}{\varepsilon_f^3.(\phi_s.d_p)^2}.V.(sen\theta + \mu_a) + \frac{(1.75.(1-\varepsilon_f).\rho_g.}{\varepsilon_f^3.(\phi_s.d_p)}.V^2.(sen^2\theta + \mu_a.\cos\theta) + \rho_b.g.(2.sen\theta - \mu_a.\cos\theta)\right].\left(\frac{\dot{v}}{g}\right) \tag{6}$$

$$\mu_a = \tan\left[(1 - 0.01\frac{V}{V_{mff}})^2 . \phi_i\right] \qquad (7)$$

where:

G	Mass flow rate, kg/h
θ	Angle of inclination of the air slide, °
μ_a	Coefficient of friction between particles and the bottom of the air slide, -
ε_f	Porosity of the fluidized bed of solids flowing in the air conveyor, -
ρ_b	Aerated bulk density, kg/m^3
ϕ_i	Particles internal friction angle, °
V, V_{mff}	Superficial velocity of fluidization and minimum velocity of full fluidization, m/s
v	Volumetric flow rate, m^3/h.

Figure 8. Air-fluidized conveyor of 1.5 m long with three outlets [6].

Table 1. Predicted solid mass flow rate according to Equation 6 [6].

Mass gas-solid flow rate for alumina fluoride (t/h) - Air Fluidized conveyor of (3"/1.5m)							Inclinação (°)
0	0	0.026	1.252	3.386	5.740	7.813	(-1)
0	0	0.132	1.380	3.562	5.962	8.075	(-0.5)
0	0	0.239	1.507	6.641	6.184	8.336	0
0	0	0.452	1.762	4.091	6.626	8.857	1
0	0	0.665	2.017	4.442	7.067	9.376	2
0	0	0.878	2.270	4.791	7.505	9.891	3
40	60	70	80	120	160	200	← Air flow rate (LPM)
0.5	0.75	0.875	1	1.5	2	2.5	← V/V_{mff}

Table 2. Experimental results from the tests runs at Albras laboratory [6].

Mass gas-solid flow rate for alumina fluoride (t/h) - Air Fluidized conveyor of (3"/1.5m)							Inclinação (°)
0	0	0	2.1488	4.7091	6.173	7.978	(-1)
0	0	0	2.825	5.871	7,633	8.649	(-0.5)
0	0	0.944	3.563	6,448	8.099	8.851	0
0	1.293	3.529	4.952	7.787	8.917	9.127	1
0	2.778	4.261	6.002	8.478	10.523	10.309	2
0	3.1926	4.829	6.208	9.764	11.497	13.195	3
40	60	70	80	120	160	200	← Air flow rate (LPM)
0.5	0.75	0.875	1	1.5	2	2.5	← V/V_{mff}

Figure 9 shows another air-fluidized conveyor (76.2 mm internal diameter and 9.3 m in length) designed using Equation 6, which was used as prototype at Albras fluidization laboratory. Equation 6 predicts a mass solid flow rate of 7.29 t/h for that air conveyor, but it was observed a mass solid flow rate of 6.6 ton/h at 1.5 V_{mff} and a downward inclination of 0.5° during the test run depicted in Figure 10. The experimental value, lower than expected, was attributed to the silo used in the laboratory, which has a storage capacity of 200 kg of fluorinated alumina. As the alumina was being consumed the mass flow rate of the conveyor decreased. This problem of continuity will not occur in an industrial application due the big capacity of the day bin.

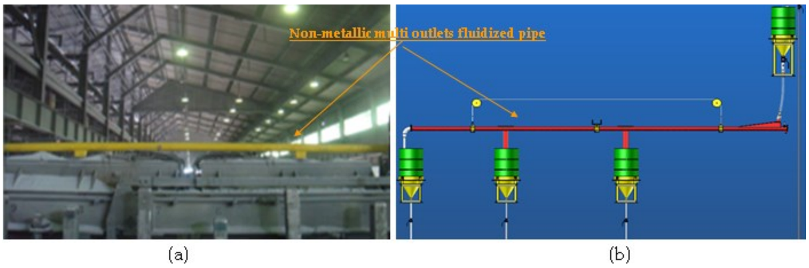

Figure 9. a) The nonmetallic fluidized pipe during tests at Albras; b) Sketch of the fluidized pipe for performance test at Albras fluidization laboratory [6].

Figure 10. Test rig of a 76.2 mm internal diameter, 9.3 m long round air slide at [6].

4. Scale-up of the Fluidized Pipeline: Application at Albras' Pot 239

Figure 11 shows the installation in July 2018 of the air fluidized pipeline with an internal diameter of 38.1 mm and 9.3 meters in length. Two men are enough to install the pipeline, designed in three sections to facilitate its installation as well as the maintenance of both the pipeline and the reduction cell itself. As the air consumption of this air fluidized pipeline is low (20 m³/h), compressed air at 50 kPa was used to test it in the production process. The mass flow rate of this air fluidized pipeline can be seen in the left-hand side of Figure 11: a theoretical figure of 2.5 ton/h of alumina is predicted for an air flow rate of 20 m³/h and an inclination of 1°. The computed value is 20 times greater than the consumption of the pot.

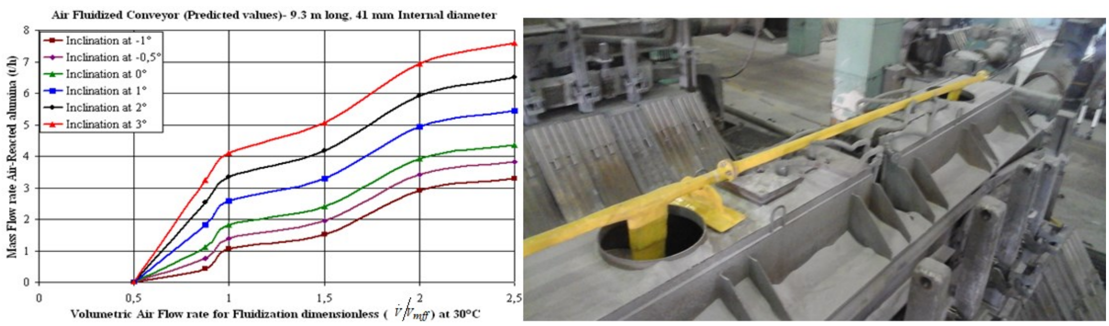

Figure 11. Predicted curves of alumina mass flow (ton/h) as a function of air flow rate and inclination angle (left) and the pipeline at erection time (right) - source [6].

4.1. Industrial Air Fluidized Alumina Conveyor Optimization

The designed air fluidized conveyor has several advantages, such as: easy to install and uninstall due to its low weight, insulating, heat resistant material, low air consumption, and, despite its small size, it shows an overcapacity compared to the pot alumina consumption. Nevertheless, alumina emissions around the pot were observed, mainly due to the employment of compressed air during field trials. The outlets of the conveyor have a length of 0.5 m, which is equivalent to a pressure drop of 4.22 kPa. The minimum pressure available by the compressed air, 50 kPa, is 11 times greater than the hydraulic wedge imposed by the column of alumina when the pot's silos are full: in this moment, the compressed air jets the alumina upwards, outside the silos. A high-level sensor was used, as shown in Figure 12, to stop the compressed air when the last silo of the pot becomes full. Alumina dust emissions in the vicinity of the pot were however observed while the pot was being fed.

Due to this environmental problem, it was decided to stop the field trial in October 2018. A new pipeline of 50.8 mm inside diameter was designed to be tested with the blower used to fluidize the conventional air slide which feeds the overhead crane silos.

Figure 12. High-level sensor used to stop the air compressed when pot's last silo was full.

In March 2019, a new fluidized pipeline of 50.8 mm was installed (Figure 13) using a deviation of the pipeline of the blower used to fluidize the conventional air slide which feeds the overhead crane's silos. The existing blower does not have a speed controller to control both flow and pressure when the pot silos are full, and it does not include an exhaust system to de-dust the pot silos during the alumina feeding process. As a result, alumina dust emissions in the pot were still detected, as can be seen in Figure 13.

Figure 13. Dust emission on Pot 239 during the alumina feeding process.

An exhaust system with covers was then conceived to capture both air and dust, therefore mitigating the emission problem during alumina feeding of Pot 239, as shown in Figure 14. The prototype remained in service until April 2019. It was then decided to design a pilot plant to feed six pots. After approval of the pilot plant tests, an industrial version for feeding two sections with 52 pots will be installed, complete with its own equipment, such as: blower with speed controller, pressure, level and air flow transmitter to control the pressure, flow and the level of alumina in the last exhausting column of system, see Figures 15 and 16.

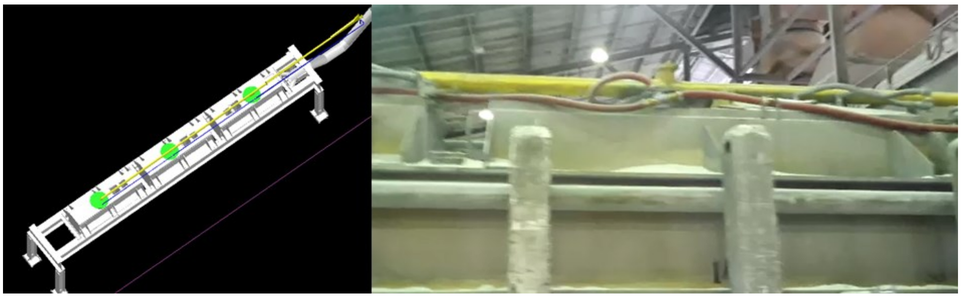

Figure 14. Pot 239 de-dust system.

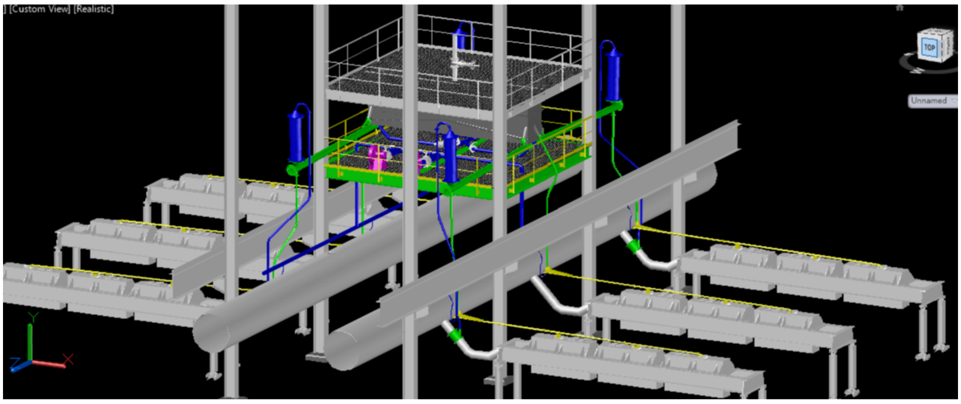

Figure 15. Pilot Plant with 6 pots and infrastructure for the future installation of 2 sections with 52 Pots.

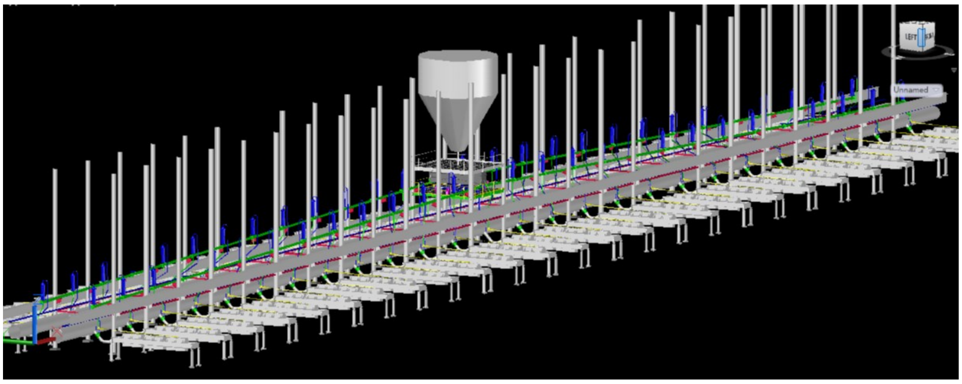

Figure 16. Overview of the installation of 52 Pots in two sections of Potroom IV of Albras.

4.2. Pilot Plant and Testing Rig Outside of Albras

Figure 17 shows an illustration of the testing rig, designed to evaluate the entire fluidized pipelines to be used at Albras pilot plant. The testing rig has the following features: speed controller, suitable instrumentation, and a supervisory system to monitor the pressures, levels and air flows in the pipelines during the whole alumina feeding process (detection of empty silos, alumina filling and high-level in the silos). Orifice plates with different size holes will be employed to balance the air flow rate from the first to the last Pot: this process is believed to guarantee an even air flow in each Pot's individual fluidized pipeline. This laboratory survey will also validate how much alumina is exhausted in the de-dust system and collected in the bag-house during an 8-hour shift cycle.

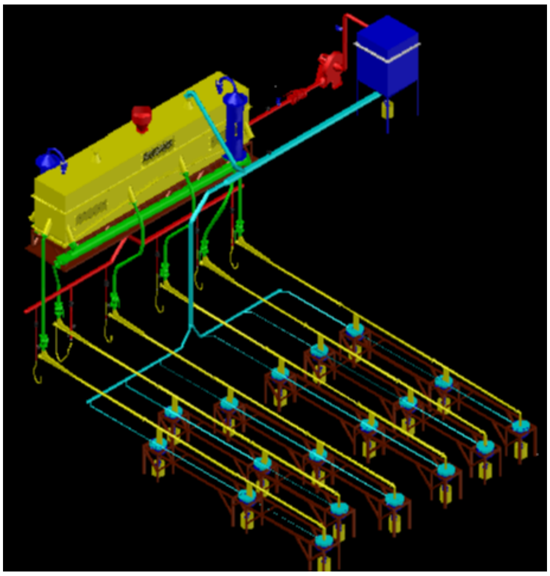

Figure 17. Overview of the test rig outside Albras.

5. Conclusions

The objective of this paper is to focus in the application of alumina continuous feeding of aluminum reduction pots at Albras, and in other aluminum smelters, with a competitive system when compared against conventional systems available on the market.

Powder handling at very low velocities, such as illustrated in Figure 3, is employed in several industrial applications. The developed equations aim to help design engineers in conceiving air slides of low energy consumption, based on the desired solid mass flow rates. In order to design an air fluidized conveyor, one must possess knowledge of the rheology of the powder that will be conveyed.

In the application at Albras, the experimental results for the small conveyor were higher than that predicted ones for horizontal and upward inclinations when considering velocities less than the minimum fluidization velocity, due to the fact that Equation 4 does not take in to account the height of material in the feeding bin. The challenges faced during the field trial with the fluidized pipeline prototype in the Pot 239 were also discussed, and the lessons learned with this experience will be useful to modify the system. The new conveyor includes a de-dust system to survey the amount of alumina collected in the bag-house and also to eliminate any alumina dust emission to the environment.

6. References

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