# Mechanical design principles and test results of a small scale airslide rig for alumina transport

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**Abstract:**

To enable online estimation and further modeling of full scale airslide capacity, a small scale rig with adjustable length was built at POSTEC in Porsgrunn. Airslide capacity (alumina flow rates) for different lengths of 3 m, 7 m and 15 m and inclination of 0 to 3.1 degrees of airslide were measured by using pressurized air in the range of 3 to 6.5 barg. It became clear that interfaces (feeding silo and standpipe) also have a great influence on the capacity of an airslide. The standpipe should be integrated into the mechanical design of an airslide, because if the material cannot be delivered (discharged) properly from the feeding unit, there is no conveying. There is a strong analogy with the flow of Newtonian or non – Newtonian fluids in an open channel which can be applied to the flow of fluidized alumina in an airslide. In this paper, the hydrological model used by Agu and Lie [2014] has been used to model alumina flow in an airslide. From the general Saint-Venant model of the open surface, a mechanistic model for non- Newtonian flow of powder in a rectangular channel has been developed. Such theoretical models based on the mass and momentum balance with bottom friction along the powder bed are numerically challenging to solve. An ODE solver in MATLAB seemed promising and showed similar trends compared to the results obtained from a small scale rig. Results so far indicated that a more detailed analysis needs to be conducted in order to find out how to tune the model parameters to further improve the model fit.

Keywords: Alumina transport, standpipe, fluidization, airslides, Saint Venant, non-Newtonian fluid.

## Introduction

In the aluminium industry, as in other many industries, pressurised air at a certain velocity is introduced by nozzles through the bottom of airslides to effect a transportation of material. The air flows upwards, passes through a porous membrane and when in contact with the bed of alumina particles, it makes the bed flow. It is known that the transport capacity depends very much on the quality of alumina, size and size distribution of the powder and powder's flowability, the angle of inclination of the airside and the amount of pressurized air distributed through the system. In the fluidized bed, the mixing and the movement of air and powder will create a flow of high complexity.  Approximately two tons of alumina are needed in order to produce one tone of aluminium. Thus the storage silos have to supply alumina at a rate of almost twice (1.93 times) the aluminium production. Hydro Aluminium uses airslides for transport of alumina over short to long distances (kilometers), for the production of aluminium. Their length depends very much on the powder handling equipment they are connected to. One of the main goals is to make the end product, aluminium metal, at lowest possible costs energy wise, while satisfying and maintaining product quality performance when it comes to raw materials (e.g.: alumina). The bulk density and the supply air pressure drop influence the alumina transport conditions, thus the capacity of the kilometers long airslides. Capacity in this context is defined as tons per hour transported alumina powder through a fixed network of airslides at fixed air flow rate and layout geometry. Ideally in order to maintain a stable airslide capacity, parameters such as bulk density, particle size distribution and rheology of the fluidized alumina powder should be monitored continuously, on line. Results from previous measurement campaigns show how changes in alumina quality quickly affect the capacity of a feeding airslide and highlights the need for better understanding of the powders fluidized rheology and transport behavior. Ideally, changes in the alumina quality should immediately be picked up by the online measurement equipment and corrected for, based on a general powder model incorporated into the control system. Thus the control system should have the capability to make appropriate corrections for each quality of alumina encountered by the process. Such a general powder model does not currently exist. When a new alumina quality is to be distributed through the system, it is standard practice for operators to take manual measurements and alumina samples. The results are communicated to the control group who then makes the adjustments manually into the control system. Previous work at Hydro, POSTEC and at the Wolfson Centre for Bulk Solids Technology in UK with characterizing the flow behavior of fluidized alumina have shown that fluidized alumina typically has a non- Newtonian behavior and that methods of defining the rheology should be established and implemented. A complimentary piece of work considering off line rheology measurements of alumina have been performed in a small fluidized column by using a standard Brookfield rheometer – the results from which will form the basis of a separate paper.

## Previous work

Stability and repeatability of gravitational flow rates from feeding silos and standpipes (addressed as interface) is crucial and needs to be achieved before one can further estimate and model the flow of alumina in an airslide. Capacity and powder quality go hand in hand with the mechanical design of the airslide and its interface. In the bulk solids community the work of Gu et al (1993) is well known. They provided experimental and theoretical evidence of the use of standpipes to increase gravity flow rates of both sand and alumina powders from mass flow bins. Their results on relatively small bore standpipes (D=44,5 mm) indicated that the effects of a standpipe attached under a bin/silo outlet would become more significant as the particle size of the bulk solid reduces and the length of the standpipe increased - provided that the standpipe would remain full of material during operation. The bulk solid discharging from the feeding silo under the effect of gravity has a self-limiting flow rate that is primarily attributed to the self-generated negative air pressure gradient within the inter-particle voids in the region of the outlet of the feeding silo.

## Test equipment

Work to evaluate flow rates from a silo was initiated in 2012 as part of an industrial PhD project between Hydro, POSTEC and the University of Greenwich. The initial configuration (2012) of the rig is shown in Figure 1 a. It became clear that the mechanical design of the outlet from the feeding silo was the bottle-neck in trying to establish stable feed conditions s. Farnish and Bradley (2006) discussed the design faults present in this configuration in terms of discharge equipment and the overall system design commonly found in industrial applications, pointing out that consistency and repeatability of discharge from vessels was the keystone to the efficiency and profitability of many types of processes. Although techniques for design of storage vessels based on the flow characteristics of particulates have been in the public domain since the 1960's, they have been slow to gain acceptance in the industry (mainly through a lack of awareness of their existence amongst engineers). According to the authors, in terms of controlling discharge from gravity flow equipment, it was often the gravity discharge approach which generated the greatest degree of variability, in terms of both quantity and repeatability. The root of the problem of inconsistent discharge rates was identified to lie with the flow channel development within the feeding silo or the discharge head. The potential causes of flow irregularities were even more critical to be aware of, in the cases where mass flow principles were to be applied, especially in the case of easy to segregate materials. Thus on systems that operated on a discharge basis that uses an adjustable outlet aperture, the development of a flow channel subject to minimal shear at its boundaries is essential. In many cases the outlet aperture relied upon the insertion of devices such as iris valves or gate valves (acting perpendicular or nearly so) to the path of the flow channel. The authors pointed out that in such cases static material would be supported from the leading edge of the valve to the nearest wall of the discharge head or vessel outlet. This supported material could extend for some distance from the outlet and generate a major shear plane of powder on powder, which again, would induce inconsistent discharge rates from the outlet – mainly by imposing core flow discharge conditions (which are characterized by inconsistency in flow rate and exaggerated segregation effects).

Figure 1 Experimental setup: a) initial 2012 design using bigger feeding silo, short pipe and iris valve, b) 2013 design using smaller silo, weight beam cells and standpipe concept.

In industry the strategy has been to increase the limiting flow rates without reducing the storage capacity of the feeding mass flow silos. Vertical standpipes often have limited application in industry due to headroom constraints commonly found in pot rooms (not enough room for cranes, rails and receiving silo/bin). Based on the previous work of Gu et al (1993), Farnish et al (2006-2012) and Dyrøy (2006), fresh measurements were carried out on a modified alumina rig at POSTEC during 2013 from which the iris valve was removed. Outlet diameter of the feeding silo was modified from 200 mm to 140 mm. A 140mm diameter standpipe (dispensing head) was installed at the outlet of the mass flow silo as shown in Figure 1 b. In order to be able to implement the mechanical changes, the upper ring of the feeding silo had to be removed due to headroom restrictions. A schematic view of the new rig is shown in Figure 2 a. The standpipe had a length to diameter ratio (L/D) of 7.5 and was connected to standard airslide segments of 3 m, 7 m and 15 m. The joint between the stand pipe and airslide was flexible to allow for testing at different downward inclinations of the airslide.

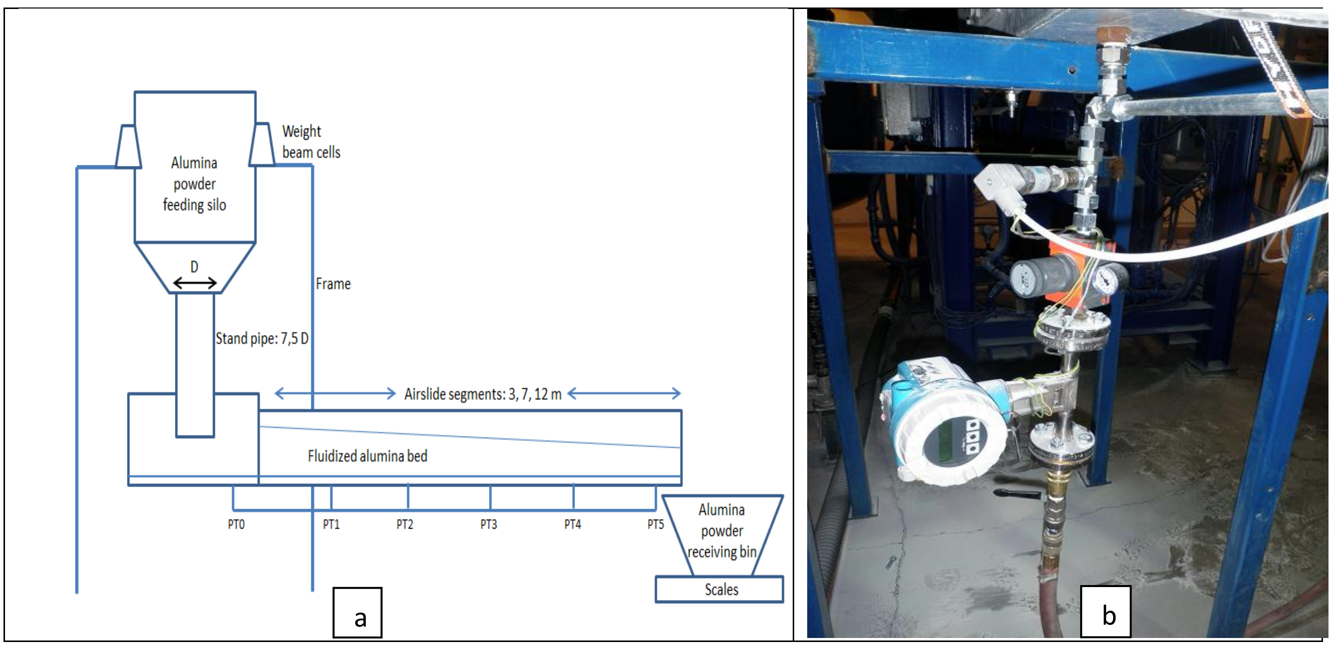


Figure 2 Schematic view of an instrumented alumina rig with: a) pressure transmitters PT0 –PT5 and b) flow meter and pressure regulator (0-6.5 barg) placed underneath PT0.

Airslide capacity for 0 to 3.1 degrees of downward inclination were measured for each segment by using pressurized air in the range of 3 to 6.5 barg. Air pressure was adjusted by using a small pressure controller as shown in Figure 2 b. Five tons alumina supplied by the Reference Centre in Årdal were used for conducting all the tests, around 500 kg being used per test round. Four consecutive tests were conducted for each operational condition (a given air pressure at a given airslide downward inclination). A hook crane was used to lift up and transport the receiving bin back and forth to the feeding silo for each test round. A butterfly valve had to manually be opened and closed for emptying alumina from the receiving bin into the feeding silo. LabView was used to record and display data from the flow meter, pressure sensors, weight beam cells and scales. Beam cells and scales are simple weighing devices, thus the values of loss and gain in weight have been calculated by filtering the electrical signals from load cells. The loss in weight for the feeding silo mounted on a frame equipped with beam cells and gain in weight for the receiving bin placed on scales were recorded by measuring the mass variation in the feeding silo/stand pipe and receiving bin versus discharge time. The feeding silo and airslide (receiving bin) capacities calculated by differentiating the mass curves with respect to time were displayed online in LabView. It was known from previous work that the stand pipe had to remain full of product at any time during operation in order to achieve stability and good repeatability of test work. It was found that the weight of the powder in a full stand pipe was approximately 50-60 kg, thus each test was to be run until 60 kg of powder would remain in the system and then manually switch off the pressurized air and stop the test. The previous work of Gu (1993) played an important role in showing how the main parts: feeding silo, stand pipe and airslide of a transport system are integrated together. The standpipe is an important part of the system acting as interface between the feeding silo and the airslide. An example of on line measured and estimated capacities for a given set of specified parameters for a test round is shown in Figure 3.

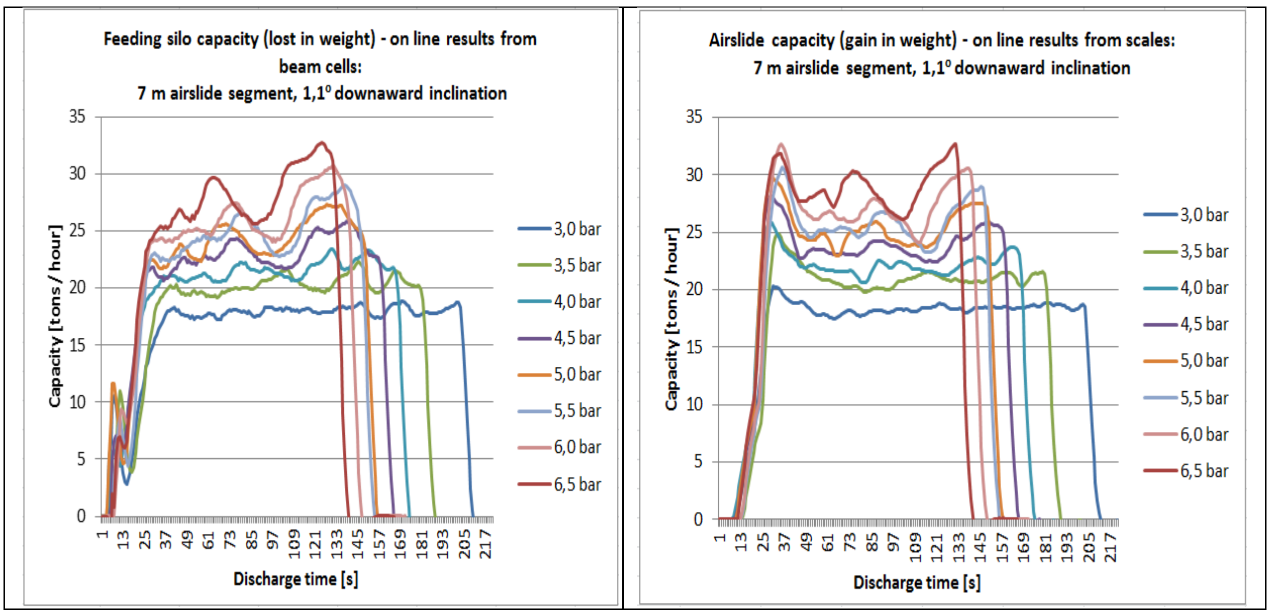


**Figure 3 On line LabView results for a set of specified operational parameters.**

## Experimental test results

In this investigation the dimensionless air velocity factor $U_0/U_{mf}$ has been varied from the start up value of 0.99, which corresponds to the minimum fluidization velocity of alumina powder, $U_{mf}$ of 0.68 cm/s, up to an upper limit of 2.14. A comparison of capacity results from the initial rig and the modified rig is shown in Figure 4 a and b.

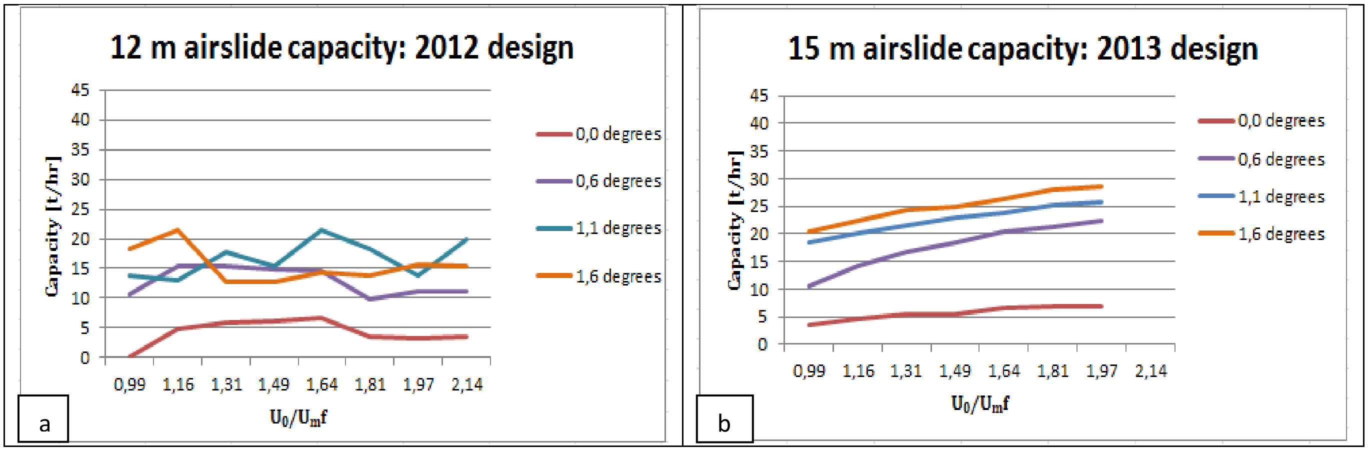


Figure 4 Capacity measurement results: a) 2012 design on 12 m airslide, b) 2013 design on 3 + 12 m airslide.

Improvements were immediately apparent on the modified rig. The flow rate of alumina increased when increasing the length of standpipe from 1D to 7.5 D by 190 % ( similar to what had been reported by Gu et al (1993)), due to the positive air pressure gradient developed at the feeding silo outlet. Improved stability of flow was also achieved, results from an average of three consecutive tests for each operational condition, show a decrease of the coefficient of variation from 3 to 40 % down to ca. 1.2 % (Table 1). Stability increased by 90 % using a 7.5 D long pipe.

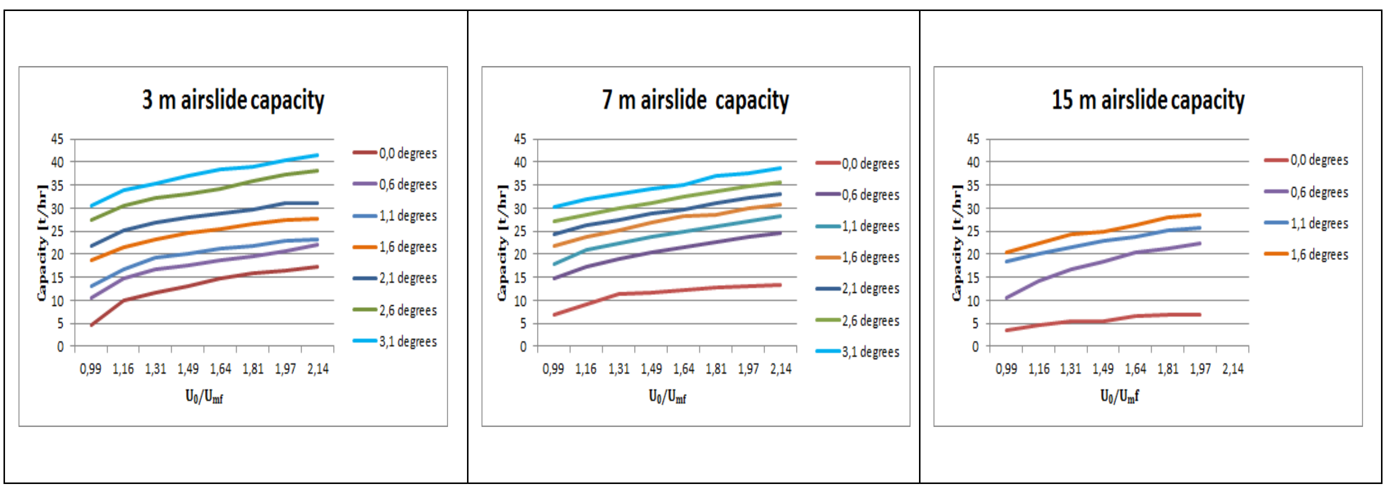


Figure 5 Airslide capacity results for a set of operational parameters in 3, 7 and 15 m long airslides.

Table 1 Coefficients of variation for the capacity of feeding silo/standpipe and airslide at 1.1 degrees downward inclination.

| 1,1 degrees | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| $U_o/U_{mf}$ | 3 m | | | | 7 m | | | | 15 m | | | |
| | Capacity [t/hr] | | Coefficient of variation [%] | | Capacity [t/hr] | | Coefficient of variation [%] | | Capacity [t/hr] | | Coefficient of variation [%] | |
| | Airslide | Feeding silo | Airslide | Feeding silo | Airslide | Feeding silo | Airslide | Feeding silo | Airslide | Feeding silo | Airslide | Feeding silo |
| **0,99** | 13,1 | 13,2 | 2,1 | 2,1 | 17,9 | 17,7 | 3,1 | 1,6 | 18,4 | 17,0 | 5,0 | 0,6 |
| **1,16** | 16,8 | 16,9 | 1,1 | 1,1 | 20,9 | 20,4 | 0,1 | 0,5 | 20,0 | 19,3 | 5,6 | 0,7 |
| **1,31** | 19,3 | 19,5 | 1,5 | 1,7 | 22,3 | 21,7 | 1,3 | 1,0 | 21,5 | 20,6 | 3,1 | 1,3 |
| **1,49** | 20,2 | 20,3 | 1,6 | 1,8 | 23,8 | 23,1 | 0,5 | 0,8 | 22,9 | 21,4 | 1,3 | 1,6 |
| **1,64** | 21,3 | 21,4 | 2,8 | 2,8 | 24,9 | 24,3 | 0,4 | 0,1 | 23,9 | 22,7 | 1,1 | 1,1 |
| **1,81** | 21,8 | 21,9 | 0,4 | 0,2 | 26,1 | 25,2 | 1,6 | 0,9 | 25,1 | 23,6 | 0,5 | 0,1 |
| **1,97** | 22,9 | 22,9 | 1,0 | 0,9 | 27,0 | 26,2 | 0,6 | 0,7 | 25,8 | 24,2 | 0,5 | 0,6 |
| **2,14** | 23,1 | 23,2 | 2,1 | 1,2 | 28,4 | 27,6 | 0,6 | 0,7 | | | | |

## Steady State Saint Venant model

There is a strong analogy with the flow of Newtonian or non – Newtonian fluids in an open rectangular channel which can be applied to the flow of fluidized alumina in an inclined airslide. The flow of fluidized alumina in an open channel can be described by the one dimensional Saint Venant mass and momentum equations as presented in Agu and Lie (2014):

$$\frac{\partial A}{\partial t} + \frac{\partial Q}{\partial x} = 0$$

$$\frac{\partial Q}{\partial t} + \frac{\partial (\frac{\beta Q^2}{A})}{\partial x} = gAsin\theta - gAcos\theta \frac{\partial h}{\partial x} - gAS_f$$

where:

Q [$m^3$/s] is the volume flow rate of alumina;

A [$m^2$] is the alumina flow cross sectional area;

h [m] is the height of the alumina bed (free surface level) measured when the flow stopped;

$\theta$ [degree] is the angle of downward inclination of the airslide;

g [$m/s^2$] gravitational acceleration;

$\beta$ is the momentum correction coefficient;

$R_h$ [m] is the hydraulic radius;

$\tau_y$ is the yield shear stress [Pa];

V=Q/A [m/s] is the calculated average flow velocity;

n is fluid consistency index, where $\varepsilon = \frac{1}{n}$;

K is flow behavior index [$Pa.s^n$];

$S_f$ is the frictional slope given by:

$$S_f = \frac{\tau_y}{\rho g R_h}\left[1 + \left(\frac{(\varepsilon+1)(\varepsilon+2)|V|}{(0.74+0.656\varepsilon)\left(\frac{\tau_y}{K}\right)^{\varepsilon} R_h}\right)^{\frac{1}{\varepsilon+0.15}}\right]$$

At steady state $\lim_{t\to\infty}\frac{\partial A}{\partial t} = 0$ , $\lim_{t\to\infty}\frac{\partial Q}{\partial t} = 0$, Q is constant and $\frac{\partial h}{\partial x}$ becomes:

$$\frac{\partial h}{\partial x} = \frac{Ag\left(sin\theta - S_f\right) + \beta V^2 hC}{gAcos\theta - \beta BV^2}$$

where $B$ is the width of the flow in the rectangular alumina airslide.

The denominator of $\frac{\partial h}{\partial x}$ characterizes the flow, the flow becomes critical when the denominator approaches zero value:

$$\mathrm{Agcos\theta} - \beta u^2 b = 0$$

Multiplication by $A^2$ gives:

$$A^3 g\cos\theta - \beta Q^2 b = 0$$

Thus the expression for alumina flow rate, Q becomes:

$$Q = \frac{(\cos\theta)^{\frac{1}{2}} g^{\frac{1}{2}} b h^{\frac{3}{2}}}{\beta^{\frac{1}{2}}}$$

Preliminary results (Figures 3 and 6) and simulations with $K = 1.35$, $n = 0.51$, and $\tau_y = 1.76$ show good agreement between the model and the on line measurements of the alumina flow rate, Q for the steady state situation. Table 6 shows simulation results for a bulk density of 950 – 1000 kg/m$^3$, where $h_0$ is the height of the bed and $Q_0$ is the capacity at the inlet.

The model needs further calibration and tuning.

| 1,1 degrees | | | | | | | |
|---|---|---|---|---|---|---|---|
| | **Operational parameters** | | | | Average capacity [t/hr] | | |
| **Pressure** | **$U_0/U_{mf}$** | **$h_0$ [m]** | **$Q_0^{1000}$ [m$^3$/s]** | **$Q_0^{950}$ [m$^3$/s]** | **Measured** | **Simulated$^{1000\text{-}950}$** | **Error$^{1000\text{-}950}$** |
| **3,0** | 0,99 | 0,126 | 0,00479 | 0,00504 | 17,9 | 17,2 | 3,7 % |
| **3,5** | 1,16 | 0,119 | 0,00580 | 0,00611 | 20,9 | 20,9 | -0,1 % |
| **4,0** | 1,31 | 0,118 | 0,00611 | 0,00643 | 22,3 | 21,9 | 1,7 % |
| **4,5** | 1,49 | 0,110 | 0,00658 | 0,00693 | 23,8 | 23,7 | 0,4 % |
| **5,0** | 1,64 | 0,110 | 0,00695 | 0,00732 | 24,9 | 25,0 | -0,2 % |
| **5,5** | 1,81 | 0,102 | 0,00731 | 0,00769 | 26,1 | 26,3 | -0,9 % |
| **6,0** | 1,97 | 0,109 | 0,00747 | 0,00786 | 27,0 | 26,9 | 0,4 % |
| **6,5** | 2,14 | 0,113 | 0,00785 | 0,00826 | 28,4 | 28,3 | 0,4 % |

**Figure 6 Simulated results for 7 m long airslide, 1,1 degrees downward inclination.**

## Conclusions

The use of the standpipe concept to increase flowrate during gravity discharge and to achieve stability of flow has been examined experimentally in a small rig at POSTEC by using similar concepts as what Gu et al (1993) had used in their work. The results of the measurements indicate that the concept, originally investigated for a standpipe of D = 44.5 mm, applied to a wider standpipe of D = 140 mm gave similar increase in flow rates and stability of flow. The standpipe is efficient only if it is kept full of powder, the feeding silo acting more as a buffer for the standpipe. This can be achieved by monitoring the weight of material in the standpipe and the flow rates of alumina on line. Thus the effect of interfaces, the feeding silo and the standpipe should be considered and included into further design of mechanical equipment, by balancing headroom availability in potrooms versus increase in transport capacity of bulk solids to optimize production. The concepts tested on the small scale rig are useful for further implementation on full scale equipment. The possibility of using non-Newtonian fluid flow behavior and Saint Venant equations was investigated. The analysis was based on the subcritical steady state flow conditions in the airslide. The model needs further calibration and tuning.

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