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EVALUATION OF THE RESTRICTED AIR ENTRY ON THE DISCHARGE RATE FROM SILOS

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Abstract. *Storage and distribution of solid materials, as well as control under powder discharge, has been fundamental to ore transportation and lately, Additive Manufacturing (AM). AM demands fine powders materials to be fed with high accuracy, by hoppers. It is not only the reliability of flow that becomes important but also to have a trace of repeatability of material discharges and flow characteristics. In this perspective, two types of hopper feeders have been utilized the most: screw feeder and scraper feeder. In the present work, the characteristics of a steady granular flow through an orifice in scraper feeders with a flat and conical bottom have been experimentally investigated under the influence of top ventilation. The discharge rate of granular particles of magnesium, alumina, glass beads and crushed glass have been studied as a function of the outlet diameter and the ventilation configuration. Tests were performed three times under the same configuration, which consisted for both apparatuses, a measurement of discharge time and the mass through outlet orifices of 15, 30 and 50 mm, with different vent area percentage. The results have shown that the discharge rate increases with the increasing outlet diameter and top ventilation in the majority of the materials studied. In both hopper geometries, a rise in mass flow rate was generally observed when ventilation was added to the system, even though the difference when doubled the vent area was not significant.*

Keywords: *Granular flow, Discharge rate, Bulk solids, Ventilation.*

1. INTRODUCTION

The impact of granular flow in daily lives is often understated, yet grains represent the second most common material displaced by humans (Kabla and Senden, 2009). In recent years, the area of bulk solids has been studied and a few centres have specialized in this field around the world (Ahn *et al.*, 2008). Storage and distribution of material, as well as control under powder for constant and precise discharge, is fundamental to food, ore, pharmaceutical industries, and any industrial application with solids handling (Suri and Horio, 2009). In this perspective, the advance of manufacturing processes that require powder feed lines such as in Additive Manufacturing (AM) of metals machinery, bulk solids handling becomes an interesting field of study for AM processes as Directed Energy Deposition (DED).

Some bulk and particle properties are fundamental for a better understanding of bulk solids challenges, and these properties include particle size and shape; size distribution; bulk densities; cohesive and friction properties; air permeability; flowability; explosibility; toxicity; and compressibility (Beverloo *et al.*, 1961). According to Ahn *et al.* (2008), particle size, shape and surface area together determine a very large extent in the degree of particles with the surrounding fluid. Materials within a particle size range in between 100-1000 μm are classified as a granular solid and are characteristic of easy flowing with cohesive effects at high percentages of fine particles (Schulze, 2008).

According to Bradley *et al.* (2001), a powder is compacted by its overburden, impact, and vibration of a storage structure. This compaction causes some powders to gain strength by cohesion and due to that, when the discharge gate is opened, some of the powder at the bottom of the hopper falls out. This procedure alters the powder distribution in the remaining material and this rearranging is the basic to explain the majority phenomena occurring during hopper discharge. In general, there is a small significant effect on the discharging mass flow rate decreasing as voidage in the material increases (Schulze, 2008).

Reynolds principle of dilatancy says that it is likely that a dilatation wave passes up through the bed for flow to proceed, i.e. a granular packing tends to expand as it is deformed, therefore increasing the amount of porous space (Kabla and Senden, 2009). Indeed, the intuitive interpretation is that voidages are required in the material for its particles to rearrange (Hecke, 2015). Bradley *et al.* (2001) affirms that voidage of a flow system is independent at bed depth, grain velocity, tube roughness, and tube diameter when it exceeds 20 particle diameters. In this perspective, for achieving a steady flow configuration, it is imperative to allow free access of air to the upper surface of the column during experiments with fine granules, which can either be by natural ventilation or pressurized conveying lines.

The flow of coarse-grained materials, which have fewer, larger discrete components than fine-grained materials, was studied by Verghese and Nedderman (1995). In their study, the mass flow rates of coarse materials though non ventilated conical hoppers followed the Beverloo equation, where the mass flow rate is proportional to D2.5 - the outlet diameter, D (Beverloo *et al.*, 1961; Verghese and Nedderman, 1995). In terms of dispenser design, conical bottom hoppers are found to be the most common for pressurized tanks due to its efficacy in prevent bulk packing and so, the formation of dead zones (Farias and Irons, 1986). Still, when studying the fundamentals of air entry and its influence on the discharge rate, very low air rates could halve the solids flow rate of the sand (e.g. 6 cm^3/s) (Verghese and Nedderman, 1995; Bradley *et al.*, 2001), so it is fundamental to allow free air entry throughout discharge of fine granules.

When it comes to applications that demands fine powders materials to be fed with high accuracy, as in AM hoppers, it is not only the reliability of flow that becomes important but also to have a trace of repeatability of material discharges and flow characteristics (Farnish, 2017). This can be achieved by pressurizing the feed line to conveying powder from hopper to the deposition nozzle in DED and general laser cladding machinery. In this perspective, two types of hopper feeders have been utilized the most: screw feeder and scraper feeder. The limits in the application of screw feeder are known to be in wear and tear, whereas for scraper feeder the hole size restrains the powder discharge (Xi-chen *et al.*, 2002).

Farias and Irons (1986) evaluated the influence of pressure inlet in a screw feeder over the flow of different particle size materials. In their rig, both gas and solids flow rate were controlled by the hopper bottom orifice diameter, the pressure drop, and the gas supplied to the conveying line. The solids feed rate was measured by a load cell displaced underneath the discharge valve. It was found that there was no change in solids flow rate with the increase in tank pressure, which was attributed to the equalization lines of powder flow, ensuring no difference to drive the powder from the hopper. However, solids flow rate can be changed in steps during the injection while maintaining the gas flow rate. Thus, the pressurized screw feeder allows independent control over gas and solids feed rates, being feasible when good control over powder feed rate is required.

A coaxial powder feeder was designed by Xi-chen *et al.* (2002) in order to increase the powder catchment efficiency in DED applications. The purpose was achieved by lowering process cost with carrying gas and proposing the free-falling motion of powder particles from hopper to the designed deposition nozzle. In their study the powder flows from a scoops feeder (Xi-chen *et al.*, 1996), direct to the deposition nozzle without carrying gas. It has been found that the developed nozzle along with the scoops feeder increased the powder catchment efficiency to 75%, in comparison to conventional nozzle with carrying gas. Also, this methodology was found suitable for DED applications when using four paths of feed powder in free-falling motion from hopper to deposition nozzle.

The present work is concerned with a continuous flow through two different scraper feeders designed with a flat and conical bottom, in which the materials flow under effect of restricted air ventilation. In this regard, discharge rates of a size distribution of granular particles of glass beads, crushed glass, alumina, magnesium and a mixture of alumina (30%)-magnesium (70%) through the configured outlet diameters of 15, 30 and 50 mm were investigated under the configuration of restricted air ventilation. This study was developed as a first step to understand and estimate the powder discharge characteristics from hoppers and powder feed lines in DED processes. Thus, the geometry of the experimental scrapper feeders may also be analyzed as in terms of dead region formation and bubbled formation throughout complete material discharge. In the following section, a brief description of the methods utilized is presented.

2. METHODS

This study investigates the air entry influence on the discharge rate from different materials through a range of outlet diameters, across core flow and mass flow configurations. A broad range of materials, grain size and shapes were used, including magnesium alloy (0.1 µm), alumina (0.3 µm), crushed glass (300 µm) and glass beads with distribution in the range of 200 µm $< d <$ 425 µm. A mixture of 30% alumina 0.3 µm and 70% magnesium 0.1 µm was also evaluated, a mixture of ceramic and metal materials.

The bulk density and the tapped density of these materials were calculated by measuring the mass of the bulk solids occupying a 1 litre volume. The mass measurement scale used in this project was an electronic balance produced by Sartorius Weighing Technology GmbH, with achieved accuracy of 0.01 g. The properties of the materials utilized are presented in Tab. 1.

The densities presented for each material indicates the mass that is necessary to occupy a litre of volume. Bulk density is the measure of mass for both, material and air, found in the vacancy within the powder particles. On the other hand, tapped bulk density consider that less air can be located in between the material particles, i.e. the powder is disposed in

Table 1. Material bulk properties

Material	Particle size (µm)	Bulk density (g/L)	Tapped bulk density (g/L)
Glass beads	200-425	1467.07	1506.38
Crushed glass	300	1299.30	1413.14
Alumina	0.3	1046.57	1149.55
Magnesium	0.1	853.55	921.60
Alumina 30% magnesium 70%	0.1-0.3	1119.04	1180.14

a more compacted way. Therefore, that explains why tapped bulk density is expected to be higher than the bulk density. For this reason, and regarding the storage conditions in silos and hoppers, tapped bulk density is the one that needs to be considered throughout the storage and further analysis.

For evaluating the mass flow rate out of discharge, two scraper feeders were developed with a flat and a conical bottom. Both hoppers were designed for having interchangeable outlet diameters of 15, 30 and 50 mm. Also, three configurations of air ventilation were tested during the material flow, which consisted in no ventilation (no orifice opened), single ventilation (one orifice with inlet diameter 12 mm) and double ventilation (two orifices with inlet diameter 12 mm). Details of both test scale hoppers designed are to be found in Fig. 1.

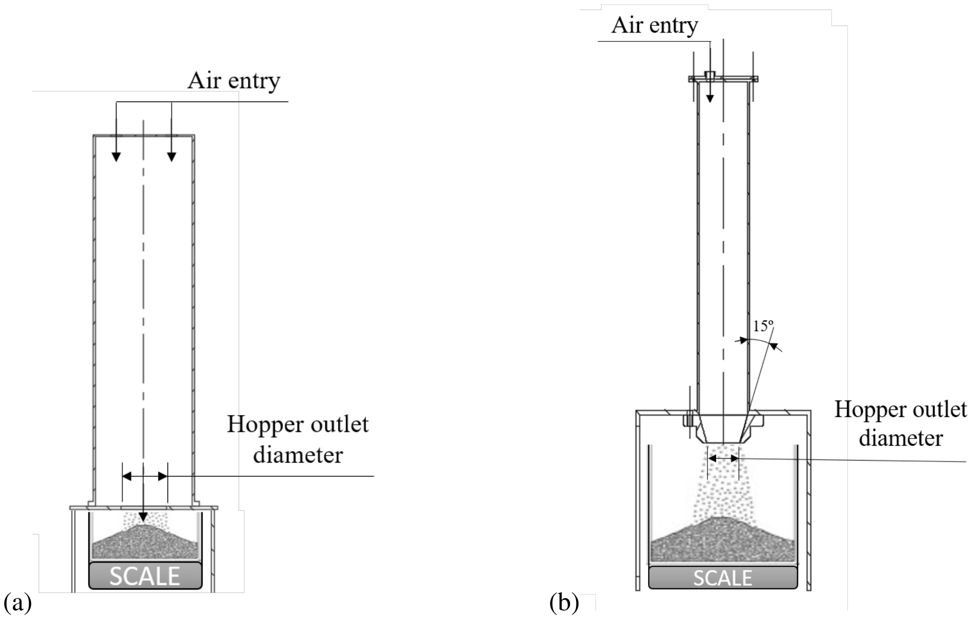

Figure 1. 3D drawing of experimental hoppers: (a) Flat bottom and (b) conical bottom

2.1 Flat bottom hopper

The scraper feeder was made from a circular acrylic tube of ø104x400 mm mounted in a flat plate and different orifices diameter for material discharges through were used. In this apparatus, two orifices of ø12 mm are at the top for external air exchange purposes. In this configuration, granular materials are stored in the tubular container until the bottom orifice for outlet discharge is opened. The bottom of the discharge tube was connected to a scale for mass measurements. Due to its maximum measurement capacity, a limited quantity of material was used. The apparatus is illustrated in Fig. 1a). The vent area can be described as a percentage of the cross section of the hopper, which gives the single ventilation and double ventilation the vent area of 1.3% and 2.6%, respectively. The experiments were performed in three repetitions for each material according to the configurations of no external ventilation, single ventilation and double ventilation for all 15, 30 and 50 mm hopper outlet diameter.

2.2 Conical bottom hopper

The scrapper feeder with conical bottom was designed in stainless steel with a tube attached to a designed top and chamber for future pressurized discharge studies. The powders flow through a conical exit carefully polished with half angle of 15°, discharging material inside a chamber that also is part of the apparatus. Due to dimension limitations, the powder discharged on a glass recipient that was placed underneath the outlet exit, being measured at the end of each discharge in a measurement scale. The powder was stored in the tubular container (Fig. 1b)with dimensions of ø72x600 mm and one orifice of ø12 mm for air ventilation at the top. As in the flat bottom hopper, only a predefined quantity of material was used due to scale limits. As in the last experiments, each material was poured in three repetitions according to the configurations of no external ventilation and single ventilation (vent area of 2.8%). The double ventilation stage was not performed in this apparatus.The stop watches used for measuring time of discharge had an accuracy of 0.01 s. Afterwards, the mass was measured and so the average mass flow rate was calculated.

3. RESULTS AND DISCUSSION

The discharge rate of the materials under the different air entry configuration for the flat bottom hopper set of experiments is plotted against the 15 mm, 30 mm, and 50 mm outlet diameter in Fig. 2. In the data presented in this section, bar plot represents the average discharge rate whereas the error bar shows the distribution within two standard deviation. The discharge rates are characterized by three regimes.

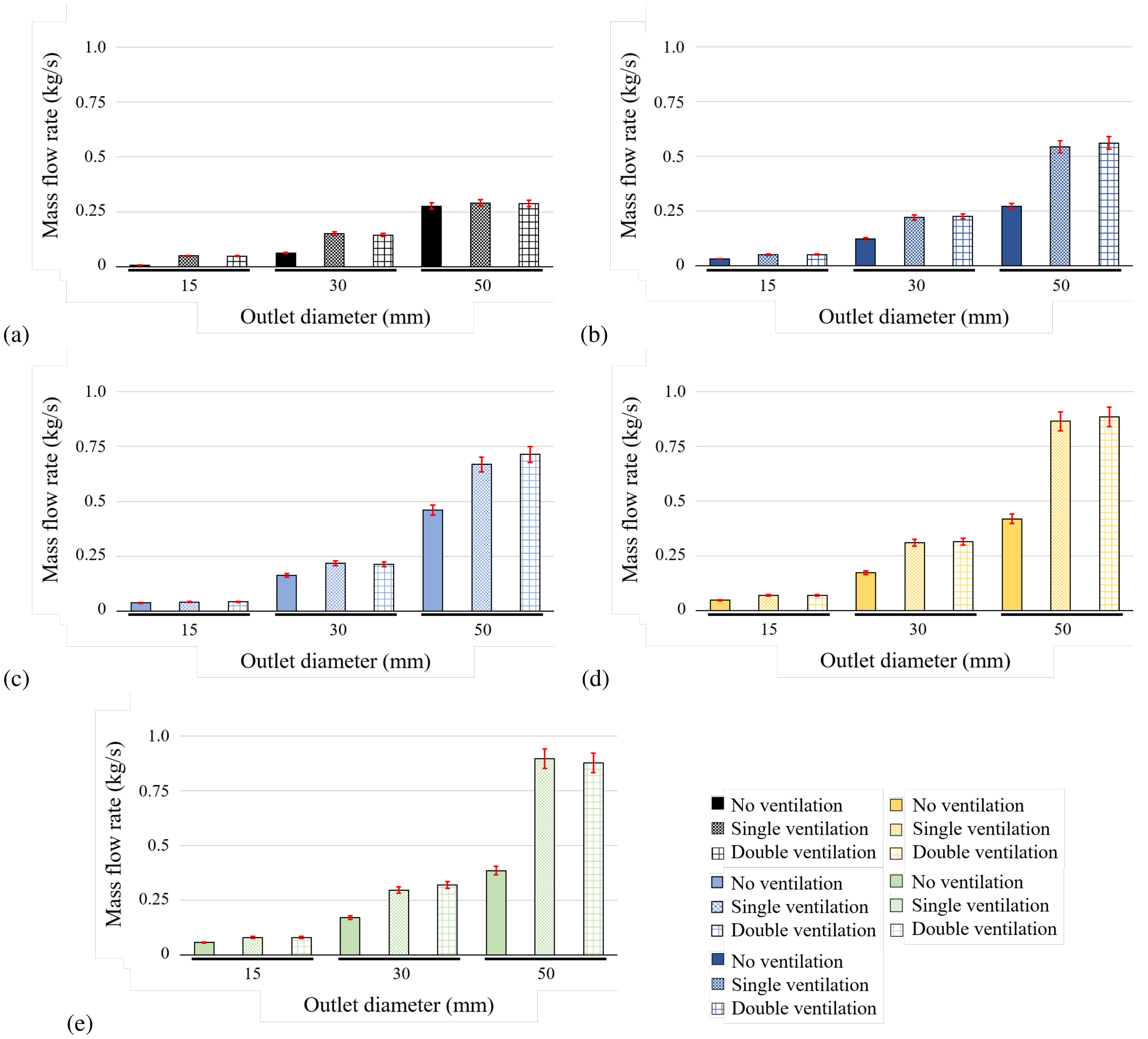

Figure 2. Mass flow rate versus ventilation and outlet diameter configurations for alumina (a), alumina 30% magnesium 70% (b), magnesium (c), crushed glass (d) and glass beads (e) discharge in the flat bottom hopper

The data presented in Fig. 2 shows that the average of mass flow rate increases as the outlet diameter increases. Although there is not a significant difference in the discharge rate when compared configurations of single and double ventilation, the highest increase on the mass flow rate occurs when ventilation regime is added into the discharge. That can be due to the internal cohesion bonds between the particles that does not let air pass through easily, and by doing so there is not much difference in the discharge time.

Dead region was created at the end of each set of experiment using the flat bottom hopper. It was visibly observed that the angle of repose varied with the materials. As wider the outlet diameter was, less material got caught in the dead region; and the angle of repose remained the same.

Bubbles formation during powder flow were observed at the end of the discharge for crushed class, glass beads and alumina. There was also noticed the presence of stick-slip flow at the mid-end of the bulk discharge, being this behaviour observed mainly in discharge of finer metallic grains as alumina and magnesium.

The mixture 30-70% alumina-magnesium flowed at an intermediate rate between the ones performed at the alumina and magnesium discharge. Segregation was also observed, making the timing processes more difficult, once one of the materials from the mixture ended up finishing discharge first.

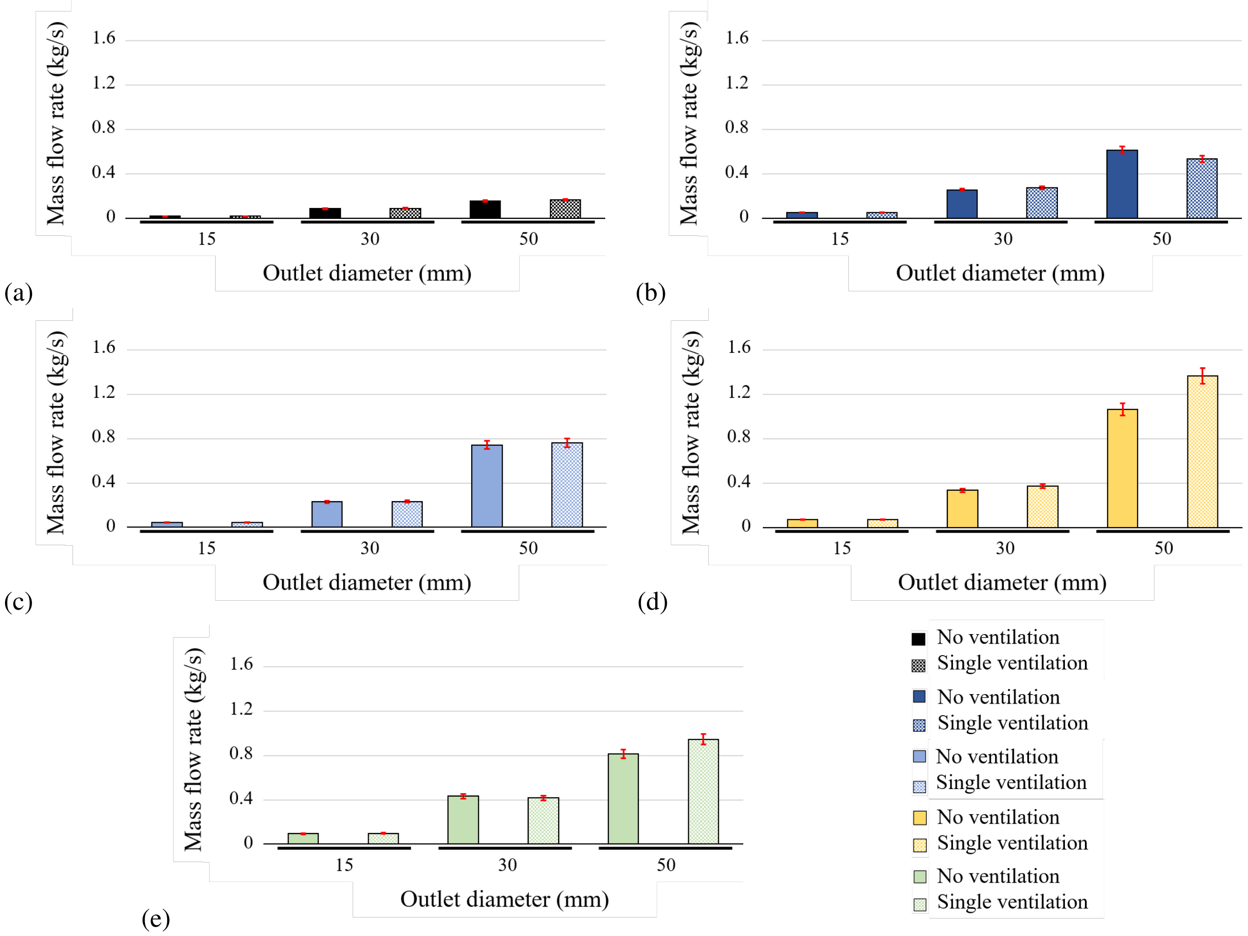

Figure 3. Mass flow rate versus ventilation and outlet diameter configurations for alumina (a), alumina 30% magnesium 70% (b), magnesium (c), crushed glass (d) and glass beads (e) discharge in the conical bottom hopper

The discharge rate of the materials under the different air entry configuration previously described for the conical hopper set of experiments is plotted against the 15 mm, 30 mm, and 50 mm outlet orifice in Fig. 3. The discharge rates through the orifice are characterized by two regimes.

In this apparatus, data also shows that the average of mass flow rate increases as the outlet diameter increases. As a result of an easy flow of air through the powder when atmospheric pressure can get into the hopper by the ventilation access, mass flow rate is observed higher when ventilation regime is added into the discharge. It was visibly observed that all the material was discharged through all the three outlet orifices. Therefore, dead region was not formed at the end of each set of experiment once it was a conical hopper.

The mixture 30-70% alumina-magnesium flowed at an intermediate rate between the ones performed at the 100% alumina and 100% magnesium discharge. Segregation was also observed, and it was a factor that made the timing processes more difficult, once one of the materials from the mixture ended up finishing discharge first.

Overall, from both hoppers design it can be outlined that the highest discharge rates were achieved by the flow of both ceramics materials. Crushed glass performed higher discharge rates due to its elevated bulk density and uniformity of particle sizes and shape, mainly when comparing to the particles of glass beads. Furthermore, from the discharge of metal powders it can be said that alumina powder discharged at the lowest rate in comparison to the mixture and magnesium, and the discharge rate from the mixture remained in between alumina and magnesium own discharge rates.

Besides, the effect of humidity in external air entry can be a limiting in the usage of air for ventilation in the discharge of fine metal powders. In this perspective, the influence of pressurization of AM feeders from DED machinery with Argon gas in the conveying of metal powders is to be investigated in future work.

4. CONCLUSIONS

Regarding the results obtained in the performed experiments, the analysis on the discharging processes, it is feasible to appoint that both bulk density and tapped bulk density are very relevant properties of powders, with higher value of density expected for tapped bulk density once the powder is found in a more compacted way. Stagnant zones were formed in the flat bottom hopper, and the angle of repose was observed to be dependent on the material properties. Bubbles formation during powder flow were observed at the end of the discharge for crushed class, glass beads and alumina. There was also noticed the presence of stick slip flow at the mid-end of the bulk discharge, being this behaviour observed mainly in discharge of finer grains as alumina. In this perspective, it can be outlined that for fines particle discharge, the continuity of flow is affected by air ventilation, once the air introduced to the system can only generate a localized aeration. Concerning the time for complete discharge, measures could be affected by the powder segregation process, once the larger particles fell firstly and then the finest grains still flowing at the end. Finally, the error associated with the measurement is estimated in between 5-10% and it is due to the measurement factor and to environmental conditions (e.g. humidity of the air, etc.), timing delay and segregation of material.

5. ACKNOWLEDGES

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