Bachelor Project

# Influence of Vibrations on Transport of Cohesive Starch Powder

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In addition, I would like to thank Professor Gernot Krammer for his valuable help and knowledge provided. You have definitely given to me the opportunity to end this stage of my academic life with a research that exceeds my expectations.

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## ABSTRACT

In this Bachelor Project, the handling of cohesive powders was studied in a laboratory feeding system by evaluating the influence of the system parameters as well as of the material moisture content. For this purpose, a vibrating chute integrated to a simple hopper was used in order to assess the cohesive powder feeding. The aim was to understand the behavior of fine powders in a feeding system, to identify the parameters involved and thus, evaluate them in a way that improved particle feeding always looking for the best performance. The latter implied obtaining a continuous and controlled flow within set limits and without the presence of possible blocks of material that could alter the mass flow leading to a greater variety of results. The project was carried out in three main steps: bibliographic review, experimentation and review of the results and main conclusions. The most relevant bibliography was studied in order to select the most influential factors that could be varied in the experimental setup, where starch was going to be used as raw material. These factors constituted the moisture content, the height between the tip of the hopper nozzle and the chute, the vibration intensity, the inclination of the system and the time and vibration for compaction. All of them resulted in a proportional relationship with the mass flow of the system, except the moisture content, which showed worsening the flowability at higher values. Therefore, with the exception of the latter, the highest values of the control parameters brought high values in mass flow (response variable), but once someone might want to have control within a mass flow range, the control parameters must be balanced. This study brings then the possibility to be extended to new work fronts that could work with other materials or similar feeding systems.

## RESUMEN

En este Trabajo de Fin de Grado, se ha estudiado la manipulación de polvos cohesivos en un sistema de alimentación de laboratorio a partir de la influencia de los parámetros del sistema así como del contenido de humedad. Para ello, se ha utilizado una rampa vibratoria integrada en una tolva simple con el fin de evaluar la alimentación de polvos cohesivos. El objetivo era entender el comportamiento de los polvos finos en un sistema de alimentación, y poder así identificar los parámetros que intervienen y evaluarlos de forma que se mejorase la alimentación de las partículas en búsqueda siempre del mejor rendimiento. Este último implicaba la obtención de un flujo continuo y controlado dentro de unos límites establecidos y sin la presencia de posibles bloques de material que pudieran alterar el flujo másico dando lugar a una mayor variedad de resultados. El proyecto se ha desarrollado en tres pasos principales: revisión bibliográfica, experimentación y revisión de los resultados y principales conclusiones. Se ha estudiado la bibliografía más relevante con el fin de seleccionar los factores más influyentes que se podían variar en el montaje experimental, donde se utilizó el almidón como materia prima. Estos factores eran el contenido de humedad, la altura entre la punta de la tolva y la rampa, la intensidad de vibración, la inclinación del sistema y el tiempo e intensidad de compactación. Todos ellos tenían una relación proporcional con el flujo másico del sistema, excepto el contenido de humedad, que empeoraba la fluidez cuando alcanzaba valores más altos. Por lo tanto, con la excepción de este último, los valores más altos de los parámetros de control trajeron valores altos en el flujo de masa (variable de respuesta), pero en el caso en el que se quiera tener un rango de flujo de masa controlado, los parámetros de control deben ser equilibrados. Por lo tanto, este estudio aporta la posibilidad de ser ampliado a nuevos frentes de trabajo que podrían trabajar con otros materiales diferentes o sistemas de alimentación análogos.

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# 1. INTRODUCTION

## *1.1* BACKGROUND: COHESIVE POWDERS IN THE INDUSTRY

In the industry handling of cohesive powders is a recurrent problem that is far from being totally solved and causes operation interruptions that are very costly for the industry. Thus, over the last years it has been an important challenge for industry looking for a solution. In the latest chemical researches, the use of additives in granular powders to improve the handling of cohesive powders was believed to be the optimal solution (YANG et al., 2005). Chemists proved that these additives enabled the reduction of adhesion and cohesion, leading to an improvement of the flowability and avoiding agglomeration. However, some analyses assessed some of the features inherent in the use of additives, which could lead to negative effects on the subsequent process steps, such as, among others, a permanent alteration of the powder characteristics. This led to new methods whose effect could be reversible and not determinant in the following process steps. A method to be emphasized is the application of mechanical vibrations (KOLLMANN & TOMAS, 2002) that don’t cause a permanent and irreversible change in the powder characteristics. A large variety of machines is used, each of them constituting a step in the whole industrial chain.

One of these devices is the so-called “hopper”, which is dimensioned to provide a favorable flow regime of the contained solid material. Cohesive powders are often assisted by vibration while stored and conveyed in hoppers in order to make a continuous operation possible.

Powder feeding constitutes of the use of different devices such as vibrating feeder, rotary valve, screw feeders, brush feeder and others, and its choice is based on criteria like material characteristics, required accuracy and process constraints. The electromagnetic vibrating feeder is a robust device widely used in the industry. It is commonly tuned to a specific working weight and in many cases works at constant vibrating frequency and variable amplitude.

A common solution for cohesive powder feeding is the use of a vibrating feeder and a non-attached hopper with an independent vibrating system, so that each step can be controlled independently and satisfactory.

Feeding cohesive powder by means of integrating a simple hopper to the vibrating chute can allow the cohesive material to flow in the hopper and still provide control of the mass flow, within certain limitations. Despite all the knowledge in powder rheology and mechanical vibration applications, it is worthy acquiring specific understanding on the use and limitations of feeding cohesive powder with an integrated vibrating system composed by a vibrating feeder and a connected hopper.

## 1.2 JUSTIFICATION

Starch in powder at different moisture levels, what implies in different cohesiveness and flowing factor, is to be fed in a gas stream. The available feeding device is a small size vibrating chute, model KF 1-2, supplier AEG (currently AVITEQ), 240V-50Hz, vibration frequency 100 Hz, tuned for a working range of 0,7 kg, but can accept a maximal working weight of 3,5 kg once tuned. The existing hopper has 765 g and no independent vibration device, and the adequate flow of starch powder through it is not possible. Hoppers for cohesive materials usually apply individual vibration systems for convenience of control.

Therefore, the attempt of using the vibration of the conveying system to the hopper can be a specific solution to be applied within certain conditions, and this study can bring understanding of feeding cohesive materials submitted mechanical vibrations at a simple integrated vibration solution.

## 1.3 OBJECTIVE

### 1.3.1 GENERAL OBJECTIVE

The general objective of this bachelor project is to assess cohesive powder feeding using a vibrating chute integrated to a simple hopper. The purpose of this evaluation is to understand the behavior of fine powders in a feeding system, to identify the parameters which influence it and thus, study them in a way that improves particle feeding always looking for the best performance. The latter implied obtaining a continuous and controlled flow within set limits and without the presence of possible blocks of material that could alter the mass flow leading to a greater variety of results. Moreover, it aims to evaluate if a simple solution of integrating a simple hopper to an existing vibrating chute can be of practical application for cohesive materials feeding, and also to know its constraints and limitations.

### 1.3.2 SPECIFIC OBJECTIVES

The achievement of the general objective described in the previous paragraph requires the development of a series of specific objectives which are developed below:

1. Evaluation of the effect of the amount of powder in the hopper on the vibration acceleration at the chute
2. Evaluation of the effect of the material moisture content on the mass flow
3. Evaluation of the influence of the vibration intensity on the mass flow control
4. Evaluation of the effect of the inclination of the chute surface on the mass outflow
5. Evaluation of the influence of the free height between the tip of the nozzle and the surface of the chute on the mass flow control of the integrated system
6. Evaluation of the effect of material conditioning (time and intensity of vibration) in the hopper on the mass outflow

# 2. LITERATURE REVIEW

Some aspects related to the proposed project that are the object of this literature review include:

- Vibrations applied to hopper for cohesive powder flow
- Electromagnetic vibratory feeder aspects
- Smartphone accelerometer for vibrations measurement
- Powder compaction in hoppers
- Setting the pace of a process - Theory of constraints

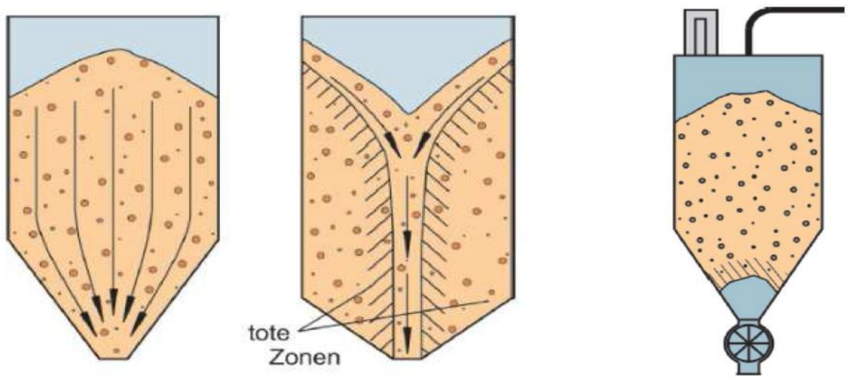
## *2.1* VIBRATIONS APPLIED TO HOPPER FOR COHESIVE POWDER FLOW

Flowability is an important aspect in the powder material storage, handling and transport process, and among different factors, moisture content can affect its flowability and stickiness. Flowability factor of powders $ff_c$ is classified as free flowing, slightly flowing, cohesive, very cohesive and not flowing for the numerical values greater than 10, between 4 and 10, between 2 and 4, between 1 and 2, and smaller than 1, respectively (SCHULZE, 2016). Maize starch and wheat starch showed a decrease in the flowability factor from 6,1 to 2,9 and 6 to 2, respectively, when moisture content was increased from 6% to 12 % (STASIAK et al., 2013). This indicates that flow in dry materials is easier, resulting in a higher mass flow than wet materials. In addition, cohesion of dry materials was around 0.04 kPa for wheat starch and 0.26 kPa for potato starch at the same consolidation stress of 10 kPa. However, in the case of wet starches, this cohesion increased to 0.65 kPa and 0.8 kPa for both materials respectively, probably leading to a decrease in the flowability. Moisture content therefore was proved to be a factor strongly influencing flowability of examined starches.

This influence could be explained by the high cohesive force among particles formed when increasing the moisture content (CHANG et al., 2014). On the assumptions that there are three kinds of free water on the particle surface (adsorbed, pellicular and capillary water), it was proved that moisture was initially adsorbed on the particle surface of OS-starch-A when its content was low, affecting the flowability of particles.

However, when the moisture content increased, high cohesive force among particles were formed causing the pellicular water formed on the periphery of adsorbed water to reduce the flowability of particles. Finally, at even higher moisture content, capillary water would form on the surface of particles leading to a further reduction of the free flowability of particles. Thus, it was found that low moisture content was favorable for a good flowability, due to the fact that cohesive forces between starch granules decreased.

Free flowing powders tend to flow under gravity effect through conical outlets, but powders that are more cohesive, for example, fine powders, tend to bridge at conical outlets and interrupt any gravity-driven flow (DUNST et al., 2018). The following Figure 1 shows the expected flow in a hopper vs. the undesired flow that in most cases presents most cohesive materials.




Expected flow Undesired flow (left: funnel flow; right: bridging)

**Figure 1**. Expected flow in the hopper versus undesired flow (SCHULZE, 2016)

The correct use of mechanical vibrations can reduce the shear strength and improve flowability (KACHE, 2009). A clear influence in the shear strength of a limestone powder can be shown in the following Figure 2 (KOLLMANN & TOMAS, 2002). This represents the pre-shear stage without vibrations with the left curve, the shear force during shear, without vibrations as well, with the second curve and the shear force during vibrated shear with the third curve.

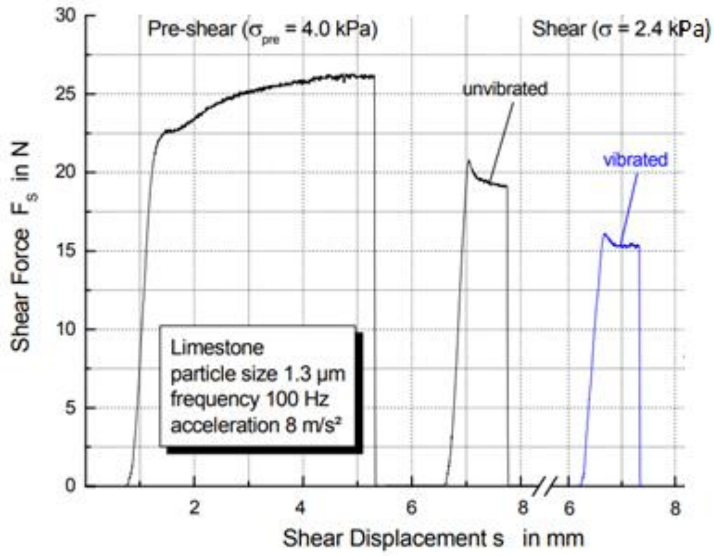



**Figure 2**. Typical shear force vs. time curves for unvibrated and vibrated shear tests, shear velocity 2 mm/min (KOLLMANN & TOMAS, 2002)

It can be noticed that the vibrations led to a lower shear force maximum at the same normal stress level. Thus, the fact that the vibrations lead to a significant reduction of the shear strength between the particles makes an improvement of the flowability, because they are less close to each other and their separation needed for a better flow becomes easier.

Rheological parameters are used for hopper dimensioning aiming for a proper material flow. The unconfined yield stress of powder materials, which characterize the cohesive forces between particles, is used to determine the hopper outlet diameter, and the wall friction angle, which describes how large the friction between the bulk material and the wall is. Both, dimeter and wall friction relate to the required hopper angle for proper material flow (ZONGQI, 2014). The unconfined yield stress $\sigma_c$ decreases with increasing vibration velocity and the wall friction angle can be reduced by applying mechanical vibration (KOLLMANN & TOMAS, 2002). The decrease of the unconfined yield stress with increasing vibration velocity can be shown for several consolidation stress levels and different materials in Figure 3.

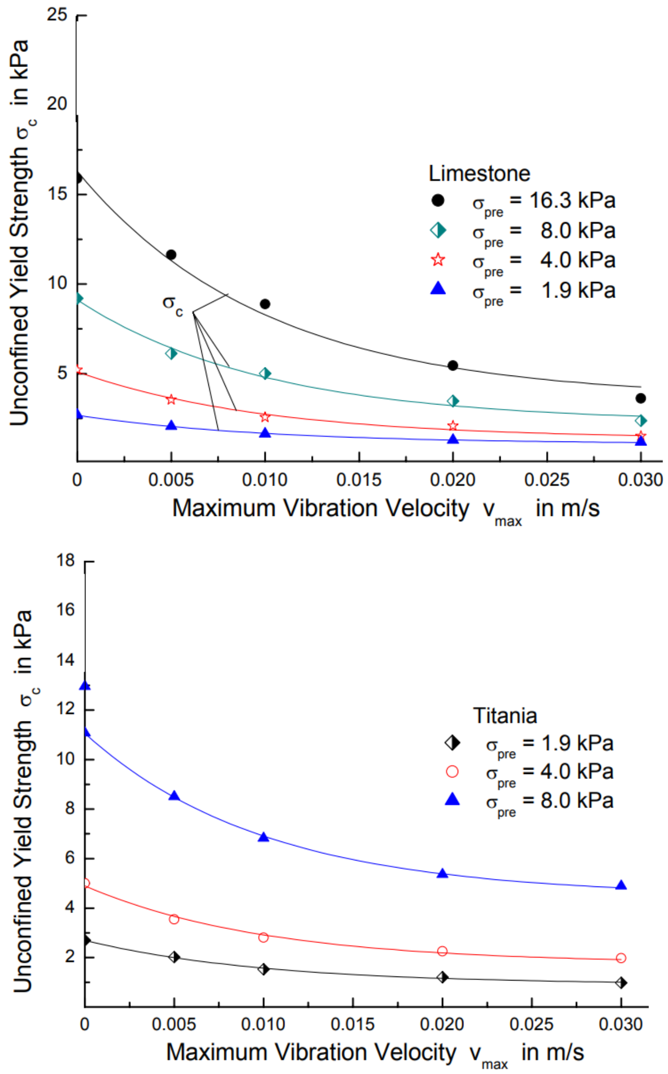



**Figure 3**. Effect of vibration during shear on the unconfined yield strength for Limestone and for Titania (KOLLMANN & TOMAS, 2002)

In Figure 3, unconfined yield strength $\sigma_c$ declines asymptotically and approaches a minimum value, when increasing maximum vibration velocity $v_{max}$.

Concerning the wall friction angle $\phi_w$, the kinematic friction between a powder and hopper wall material can be reduced by the application of mechanical vibrations (ROBERTS, 1984). This dependence can be observed in Figure 4 for limestone on stainless steel (KOLLMANN & TOMAS, 2002).

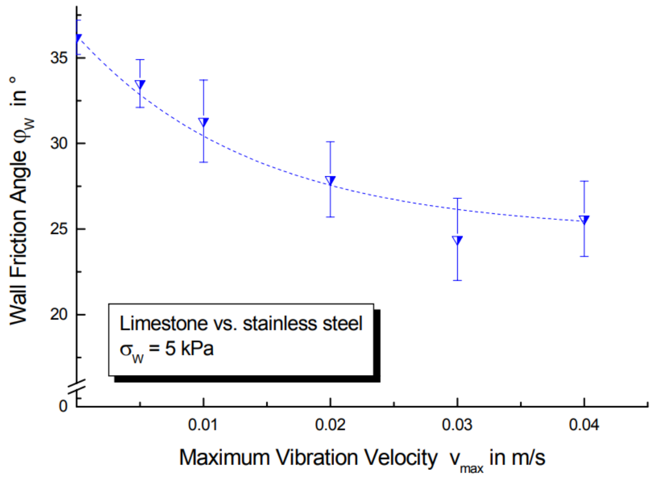



**Figure 4**. Wall friction angle vs. maximum vibration velocity (Limestone / stainless steel) (KOLLMANN & TOMAS, 2002)

As previously stated, these two rheological parameters have a consequence on hopper design (KOLLMANN & TOMAS, 2002). The minimum outlet diameter $b_{min}$ mainly depends on the unconfined yield strength $\sigma_c$. The lower the unconfined yield strength is, the smaller is the minimum outlet diameter of the hopper. Moreover, the critical outlet diameter $b_{min}$ to avoid bridging decreases with increasing vibration velocity, as shown in Figure 5. The contrary occurs with the hopper angle to ensure mass flow $\Theta$, which increases with the application of increasing vibration velocity. This rheological parameter, on the other hand, is influenced by the wall friction angle $\phi_w$; with a smaller wall friction angle, the shallower is the hopper angle.

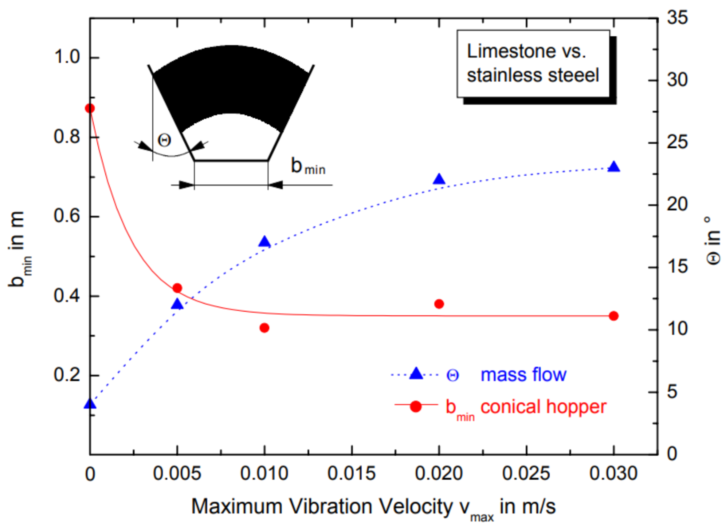



**Figure 5**. Critical outlet diameter and mass flow hopper slope vs. vibration velocity (Limestone powder / stainless steel) (KOLLMANN & TOMAS, 2002)

The flow of different powder materials were tested in an experimental vibration shear tube and results showed that different materials had different mass flow rate profile as function of vibration acceleration, with a positive correlation within the tested range (IMRAN ZAINUDDIN et al., 2012). The vibration of the tube generated a shear field and, as a result, adhesion forces between particles are overcome by forces generated in the shear field; particles lose contact and flow out of the outlet slit by the powder pressure under gravity. Thus, the mass flow rate increases with the vibration after exceeding a certain value of critical vibration acceleration. This can be seen in Figure 6, which represents the relationship between the mass flow rate w and the vibration acceleration α for different mass median diameters in μm ($D_p50$) of several materials, noted in brackets. Thus, the names of the samples are abbreviated, e.g., white fused alumina with a mass median diameter of 2 μm is abbreviated as A(2).

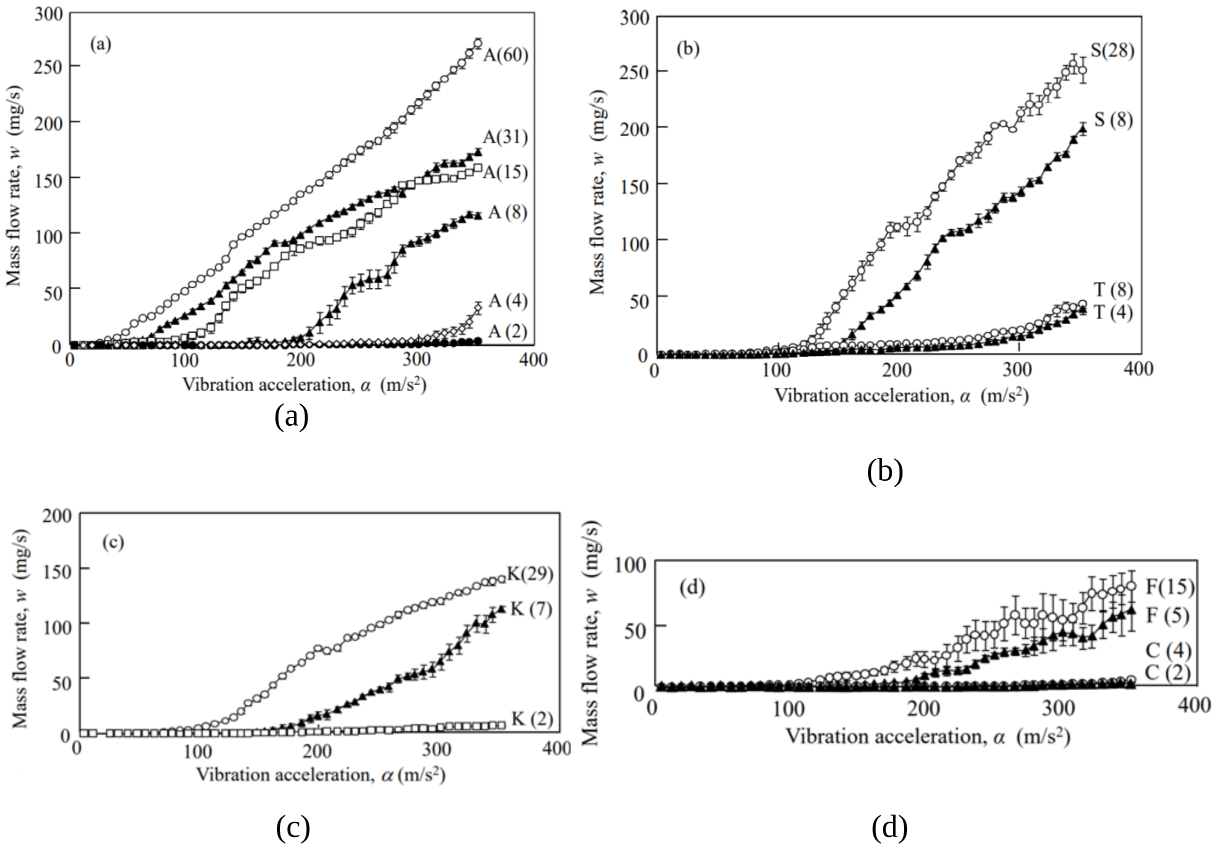



**Figure 6**. Flowability profiles of (a) white fused alumina, (b) silica sand and talc, (c) kanto loam, (d) fly ash and calcium carbonate, heavy for different mass median diameter (IMRAN ZAINUDDIN et al., 2012)

A typical dependency of particle diameter on powder flowability can be seen in Figure 6. However, powder flowability cannot be estimated only by the particle diameter but also by material characteristics such as shape, surface roughness, density, etc. On the other hand, the above mentioned is true for the four powder materials; the mass flow rate increases in effect as the vibration acceleration is higher. Therefore, controlled vibrations can be used to avoid clogging and to allow a favorable flow regime in a hopper storing and handling cohesive powder.

## 2.2 ELECTROMAGNETIC VIBRATORY FEEDERS ASPECTS

Electromagnetic vibratory feeders (EMVF) are commonly used for conveying particulate materials under controlled mass flow. Their functioning is based on a system of two masses coupled by means of an elastic component consisting of flexible leaf composite springs. A chute which conveys the material is connected to a moving assembly that vibrates while excited by an electrically driven magnetic core (DESPOTOVIC et al., 2014).

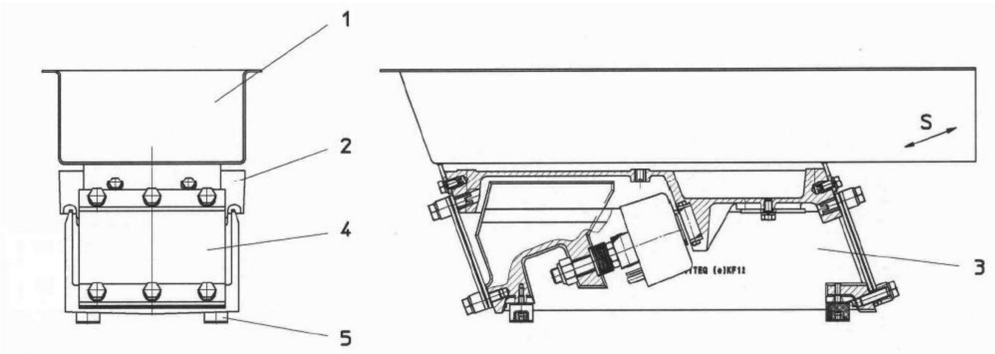



**Figure 7**. Example of electromagnetic vibratory conveyor drive main parts, vibration in s direction (AVITEQ, 2011)

The conveyor drive is a two-mass oscillation system and it is, among other things, made up of the main components: base plate (2), leaf springs (4), electromagnet (6) and lower part (3). The electromagnet (6) generates a linear-path upwardly oscillation motion. The working unit (1) that is mounted to the base plate (2), transmits the oscillation motion to the transported material. Together the base plate and the working unit form one mass unit within the oscillation system. The lower part (3) represents the counter-mass. Both masses are connected by leaf springs (4). Rubber pads (5) support the oscillation system to its case. The vibration amplitude s is produced (AVITEQ, 2011).

The particle transportation can be interpreted from Figure 8 (AVITEQ, 2021a), where the chute harmonic movement (blue line) conveys the particle while moving forward and after material takes off and detaches from the chute surface, when the chute reaches the maximal amplitude and moves back. When material lands on the surface, the chute is already close to the most negative point of its amplitude.

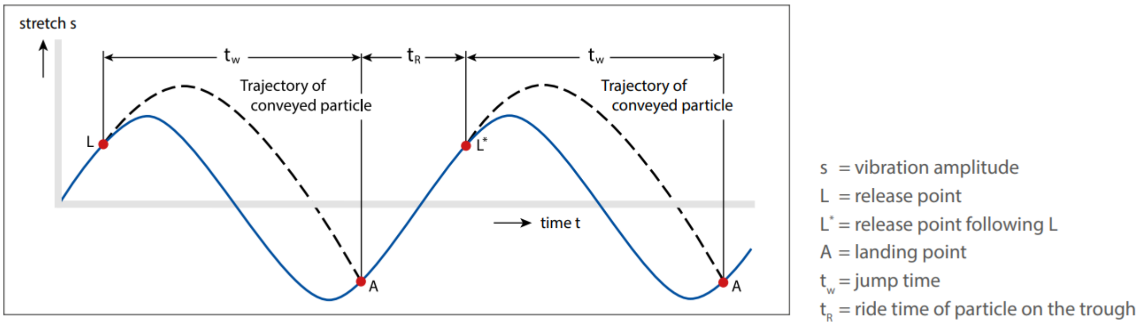



**Figure 8**. Chute harmonic movement and particle transportation (AVITEQ, 2021a)

Knowing that the friction of powders can be apparently reduced by ultrasonic vibration, many chute-like transport processes for powders could be optimized (DUNST et al., 2018). Thus, many conventional transport mechanisms like the vibratory conveyor that is studied in this section and use the principle of inertia, can be optimized using "friction reduction" by ultrasound. As an example, the setup of a powder transport principle that is based on a harmonically vibrating pipe and coordinated friction manipulation is schematized in Figure 9.

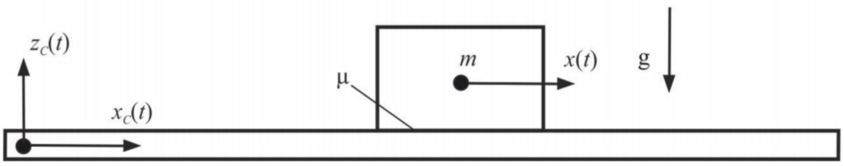



**Figure 9**. Schematic of the powder transport by coordinated manipulation of friction forces (DUNST et al., 2018)

Figure 9 shows how the powder-carrying substrate vibrates harmoniously in an axial direction $x_c(t)$ with frequency $f_a$ and amplitude $\hat{x}_c(t)$, also illustrated by [Eq. 1].

Under negative relative velocity $x'_c(t) - x'(t)$, a vibration in orthogonal direction $z_c(t)$ is superimposed, as shown in [Eq. 2], so that the effective coefficient of friction between powder mass m and pipe is reduced.

$$x_c(t) = \hat{x}\sin(2*\pi*f_a*t) \quad \text{[Eq. 1]}$$

$$z_c(t) = \begin{cases} \hat{z}_c\sin(2*\pi*f_r*t), & x'_c - x' \leq 0 \\ 0, & x'_c - x' > 0 \end{cases} \quad \text{[Eq. 2]}$$

Therefore, the powder mass is highly accelerated during time periods of positive relative velocity and slightly decelerated during time periods of negative relative velocity due to lower friction and thus moves in one direction.

Another way to see this principle specific to this type of machine can be noticed in Figure 10, which displays the axial and radial displacement of the pipe for an exemplary excitation.

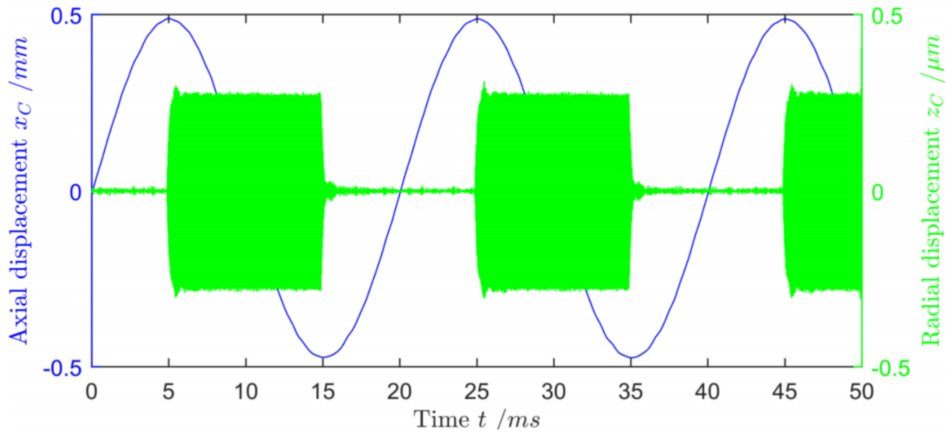



**Figure 10**. Axial and radial displacement of the pipe vibration in the powder transportation system; pipe material: aluminum alloy (DUNST et al., 2018)

The axial vibration (sinusoidal curve) has a frequency of 50 Hz, contrary to the pulsed signal, which has a radial resonance frequency of 35 kHz. Due to this high value, the transient phases are extremely short of the radial vibration, which makes the transportation possible even at much higher frequencies of the axial vibration.

On the other hand, Figure 11 shows the mean powder velocity for different excitation amplitudes of both axial and radial vibration (DUNST et al., 2018).

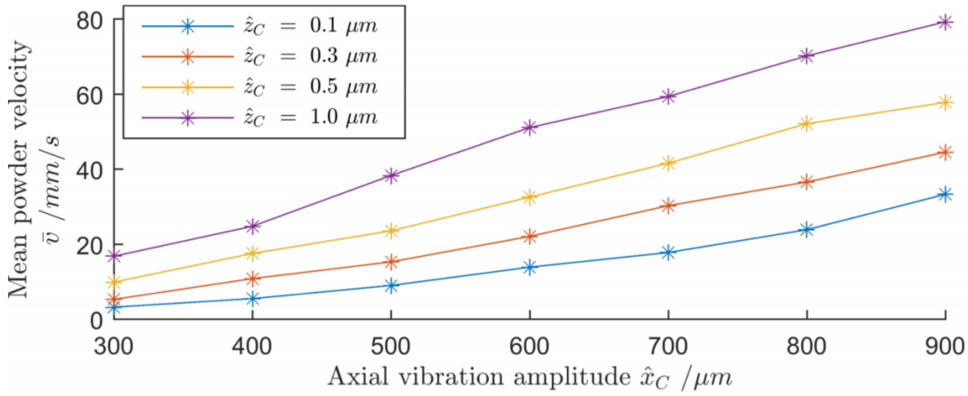
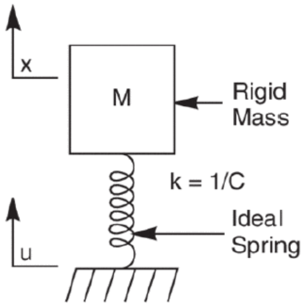



**Figure 11**. Mean powder velocity for variation of amplitudes of axial and radial excitation of the pipe; test powder: flour; frequencies fa = 50 Hz, fr ≈ 35 kHz (DUNST et al., 2018)

Powder velocity and mass-flow can be adjusted by changing the amplitudes of either the low-frequency axial vibration or the high-frequency radial vibration of the pipe as well as the pulse width of the radial vibration.

Some EMVFs work at constant vibration frequency, with variable vibration amplitude which is adjustable by means of a controller. The system is tuned to vibrate the chute at a frequency close to its natural frequency, but not at the same frequency in order to avoid resonance and damages. The closer the drive frequency is to the natural frequency of the vibrating mass, the greater will be the amplitude and the working stroke (AVITEQ, 2011).

Resonance occurs when the vibration frequency of an object due to a force is very close or even at the object's natural frequency, and in this case a great increase of the vibration amplitude is to happen (WIKIPEDIA, 2021). Conceptually, in a rigid mass and a linear spring of a simple harmonic oscillator, the natural frequency $w_0$ is a function of the mass of the rigid body M and the stiffness of the spring represented by its elasticity coefficient k, and it is obtained by [Eq. 3]. This is schematized in Figure 12.




$$w_0 = \sqrt{\frac{k}{M}} = \sqrt{\frac{1}{CM}}$$

[Eq. 3]

**Figure 12**. Harmonic oscillator and natural frequency ($w_0$) (NEWPORT, 2021)

As per the concept of the natural frequency, besides the stiffness of the system, the mass influences its natural frequency. So, as it is observed from [Eq. 3], for a given stiffness of the body, the square root of the mass is inversely proportional to the natural frequency of the system.

Studies with an EMVF showed that the initial resonance frequency of the system of 50 Hz dropped to 44.5 Hz by a sudden addition of 300 g of conveying material to the chute, generating a reduction in the vibration amplitude, as well as in the working stroke (DESPOTOVIC et al., 2014). This led to an increase of the difference between the drive frequency (50 Hz) and the new natural frequency (44.5 Hz). Figure 13 shows the compensation of the disturbance caused by the mass change of the load carrying element (LCE). In this loading process, the oscilloscopic records of LCE displacement (CH1) and electromagnetic vibratory actuator (EVA) current (CH2) are presented. At the time moment marked with the arrow (↑), LCE was suddenly filled (with sugar material mass of $\Delta mk$ = 300 g) at driving frequency $f_{drv1}$ = 50 Hz. Under these conditions, the mechanical resonance frequency of the system changed from $f_{01}$ = 50 Hz to $f_{02}$ = 44.5 Hz. Then, the drive frequency compensated (44.5 Hz), leading to a recovery of the amplitude and to a reduction of the difference between drive frequency and natural frequency.

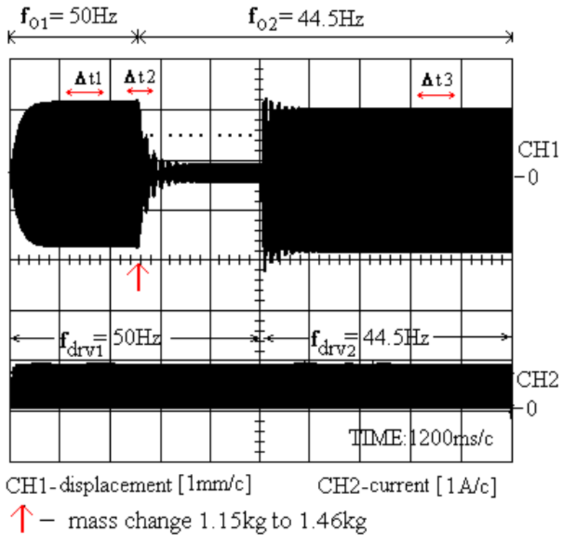



**Figure 13**. Frequency control of resonant EMVF and change mass compensation (DESPOTOVIC et al., 2014)

Nevertheless, technical practices of feeding devices supplier neglect the effect of the mass of powder for the device tuning (AVITEQ, 2021).

## 2.3 SMARTPHONE ACCELEROMETER FOR VIBRATION MEASUREMENTS

Experiments are carried out using a smartphone sensors that is available by downloading an app. Examples of applications and types of experiments can be accessed and taken as example, including measurements of vibration acceleration, that can be made by the application called “Phyphox”. Vibration acceleration is registered in x, y and z axes according to the position of the smartphone (PHYPHOX, 2021). This application enables the frequency spectrum representation (also called acceleration spectrum), using the accelerometer as a data storage device for vibrations. The vibration is the direct result, and the frequency one of the parameters of interest. In general, the real vibration curve cannot be seen, represented by Figure 14. What appears is only the moment at the acceleration for each sample for the sensor, which can be schematized by Figure 15.

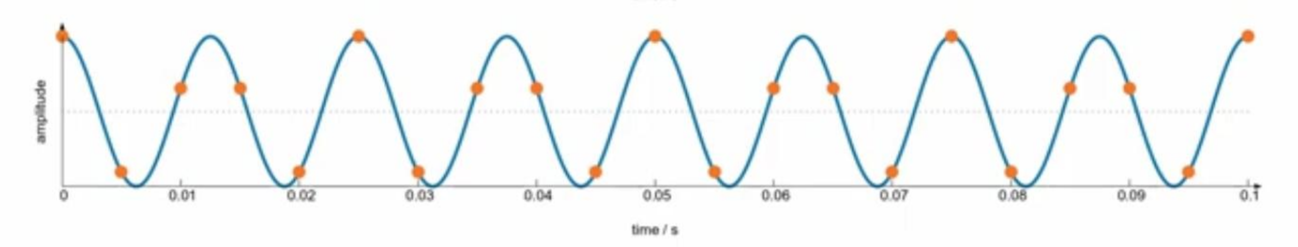



**Figure 14**. Vibration curve representing the amplitude as a function of time (PHYPHOX, 2021)

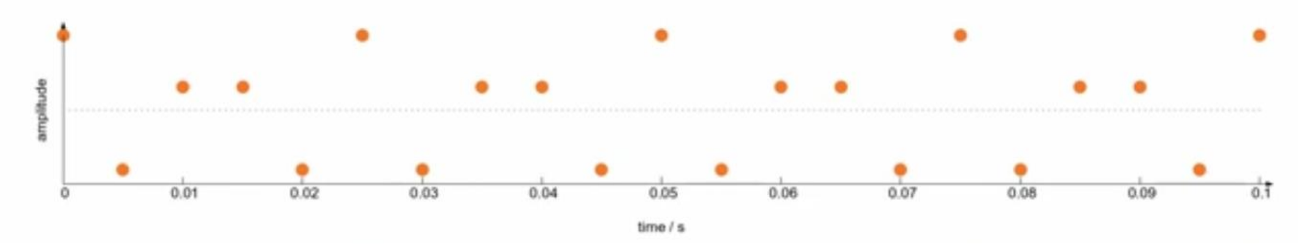



**Figure 15**. Amplitude as a function of time for each sample of the sensor (PHYPHOX, 2021)

Different researchers report the use of smartphone sensors associated to specific software or application for teaching or even research (MONTEIRO et al., 2014; MONTEIRO et al., 2020; BA et al., 2020). Besides the acceleration range of the smartphone accelerometer, one of the main issues to measure and describe the acceleration of higher frequency vibration events is its sampling frequency limitation of this resource in the smartphones. The sampling frequency of the device should be more than twice the vibration frequency, so to sample representatively within the period of the vibration, and so to follow the Nyquist theorem (BA et al., 2020).

## *2.4* POWDER COMPACTION IN HOPPERS

Consolidation of powders can happen when powders fill and occupy a vessel (MCGREGOR, 2018). From the initial moment they are filled, powders may increase their internal strength (also known as “failure strength”). Due to gravity, the self weight of powder pushes down on particles below, so powder at the bottom of the vessel experiences the highest compaction stress. At the same time, air gradually squeezes out from empty spaces between particles. Consolidation takes place as particles move closer together. Increases in powder strength between the particles depend on the amount of time the powder remains stationary and undisturbed.

In this sense, an experimental work led to the development of the “annular shear cell,” a chamber that held the powder sample, allowed it to be consolidated, and then exposed it to uniform shearing forces (MCGREGOR, 2018). As the annular shear-cell test progressed, the reduction in sample volume was measured and the powder bulk density, defined as the self-weight of the powder, was calculated. Figure 16 presents the results obtained for different powders.

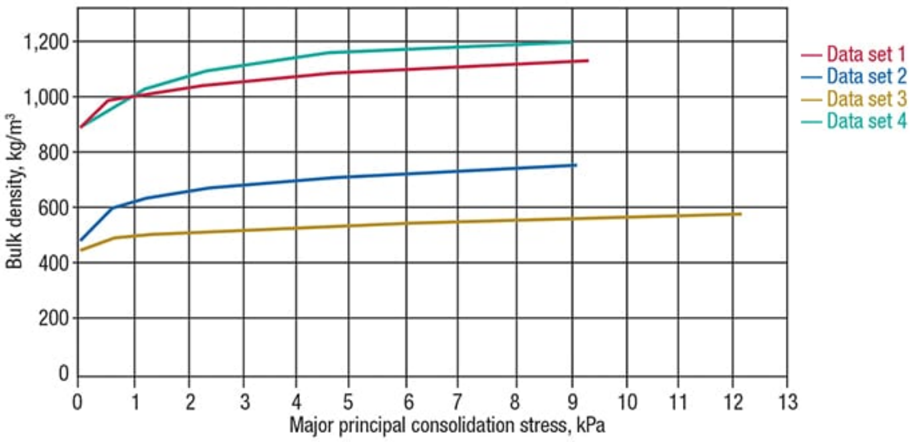



**Figure 16**. Bulk density of different powders according to the consolidation stress (MCGREGOR, 2018)

The left-most point on the graph show the loose-fill density at the beginning of the test, representing the powder condition when it was first poured into the vessel. Bulk density values increase as the consolidation stress augments and normally approach an asymptotic value as consolidation of the powder reaches a maximum.

On the other hand, vibrations are also used for powder consolidation in vessels (ANDO et al., 2010). A vibratory powder consolidation process was provided in which a powder material was subjected to high-frequency vibratory energy while under static compressive loading, resulting in a fully dense consolidated part. This consolidation resulted from material joining under high strain-rate surface and inter-particle rubbing that produced oxidation-free particle surfaces, local particle deformation and particle joining. The vibratory energy did not attenuate as the consolidation front propagated through the powder compact, because a constant amount of energy was transmitted to the consolidation front through the consolidated part of the material in which frictional loss was minimal. During the vibratory compaction process, impurities on the particle surfaces were eliminated. The high strain-rate deformation gave rise to a high vacancy concentration, which promoted consolidation through increasing rates of mass transport.

## *2.5* SETTING THE PACE OF A PROCESS – THEORY OF CONSTRAINTS

In a process with different chained and interdependent steps the process production rate is defined by the step of lower production rate (GOLDRATT, 1990). This step of lower production rate constitutes one of the multiple constraints that can present a process. This is when the theory of constraints (TOC) comes into play. This theory summarizes that every system must have at least one constraint, because if not, a real system would make unlimited profit, and also that the existence of constraints represents opportunities for improvement. Thus, TOC considers constraints as positive, not negative, due to the fact that for it, they determine the performance of a system; a gradual elevation of the system's constraints will improve its performance. In this sense, this theory of constraints is based obviously on a working principle, which provides a focus for a continuous improvement process, and which consists of five focusing steps summarized in Figure 17.

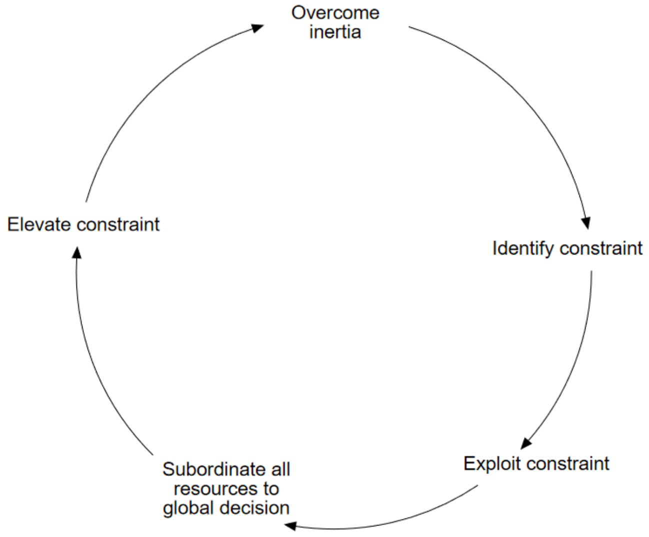



**Figure 17**. Process of on-going improvement (GOLDRATT, 1990)

As it can be seen in Figure 17, first, it is necessary to identify the system's constraints, what is needed to prioritize them according to their impact on the goal(s). Then, it is interesting to decide how to exploit them; if the constraint is physical, the objective is to make the constraint as effective as possible. In the third step, the theory proposes to subordinate everything else to the above decision, in other words, every other component of the system (non constraints) must be adjusted to support the maximum effectiveness of the constraint. In the penultimate step, system's constraints have to be elevated. If existing constraints are still the most critical in the system, rigorous improvement efforts on these constraints will improve their performance. As the performance of the constraints improves, the potential of non constraint resources can be better realised, leading to improvements in overall system performance. Finally, in the last step of the theory of constraints, it has to be assured that in any of the previous steps a constraint is broken, if not, it has to go back to step 1.

## 3. MATERIAL AND METHOD

The vibrating feeding device used in this project is a KF 1-2, 240 V – 50 Hz, manufacturer AEG, operating at a vibration frequency of 100 Hz and variable amplitude throughout a potentiometer type controller. It can be shown in Figure 18. The simple hopper is made of stainless steel (765 g) and was fixed to the chute (700 g) throughout metal fixation parts and a nozzle (546 g) assembling one unique vibrating set of (2011 g). The hopper is illustrated in Figure 19.

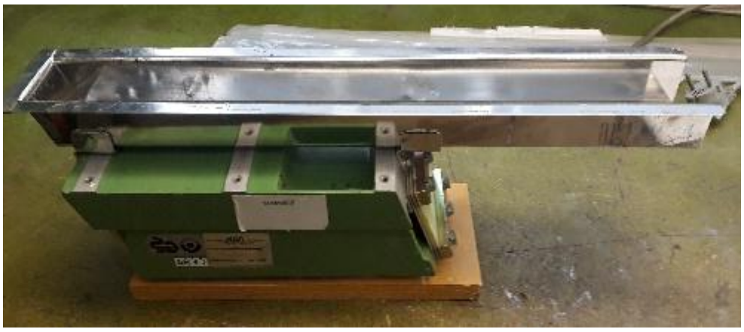


**Figure 18**. KF 1-2 vibration feeding device

| Ref. | Dim (mm) |
|---|---|
| $D_T$ | 30.2 |
| $L_T$ | 50 |
| $D_H$ | 220 |
| $H_H$ | 255 |

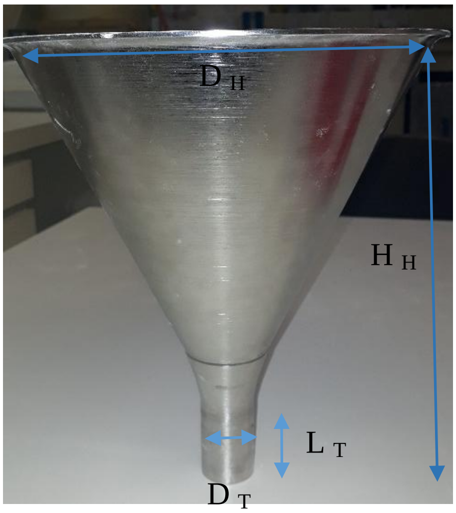



**Figure 19**. KF 1-2 Hopper

The whole integrated vibrating equipment, which integrates all the parts previously mentioned (vibrating feeding device, hopper, chute, fixation parts and nozzle) appears in Figure 20. It was tuned to 2600 g, so called working weight, being 2011 g respective to the fixed parts and the difference respective to powder mass to be initially contained in the hopper.

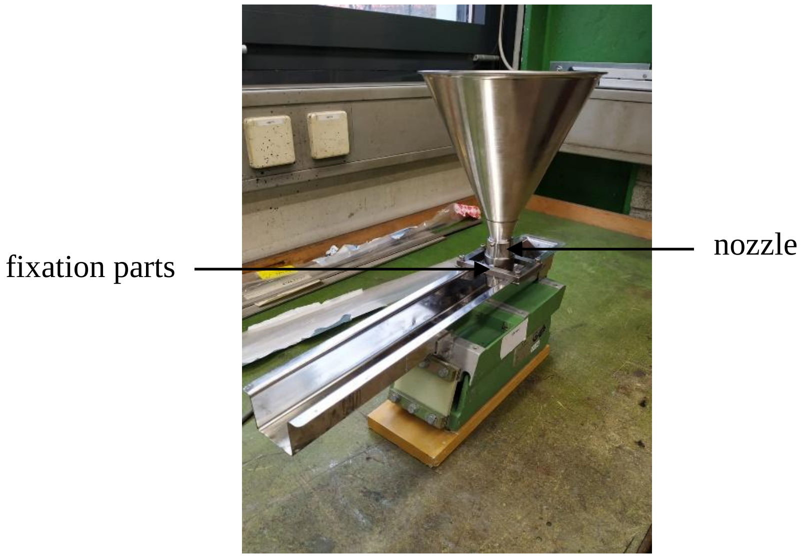



**Figure 20**. Integrated system: KF 1-2, Hopper, fixation parts and nozzle

The project encompassed laboratory activities, results and statistic treatment, and interpretation (Figure 21).

Laboratory activities comprehended the following main steps:

- Starch powder preparation at different moisture levels
- Experiments for chute vibration acceleration measurements with different powder masses in the hopper
- Experiments for determination of hopper mass outflow of starch with different moisture levels as a function of the intensity of vibration
- Experiments for assessment of the mass flow of starch with 3 different moisture levels as a function of the free height between the tip of the nozzle and the surface of the chute
- Experiments for determination of hopper mass outflow for starch with different moisture levels as a function of the inclination of the chute plane

- Experiments for assessment of the mass flow as a function of material conditioning in hopper

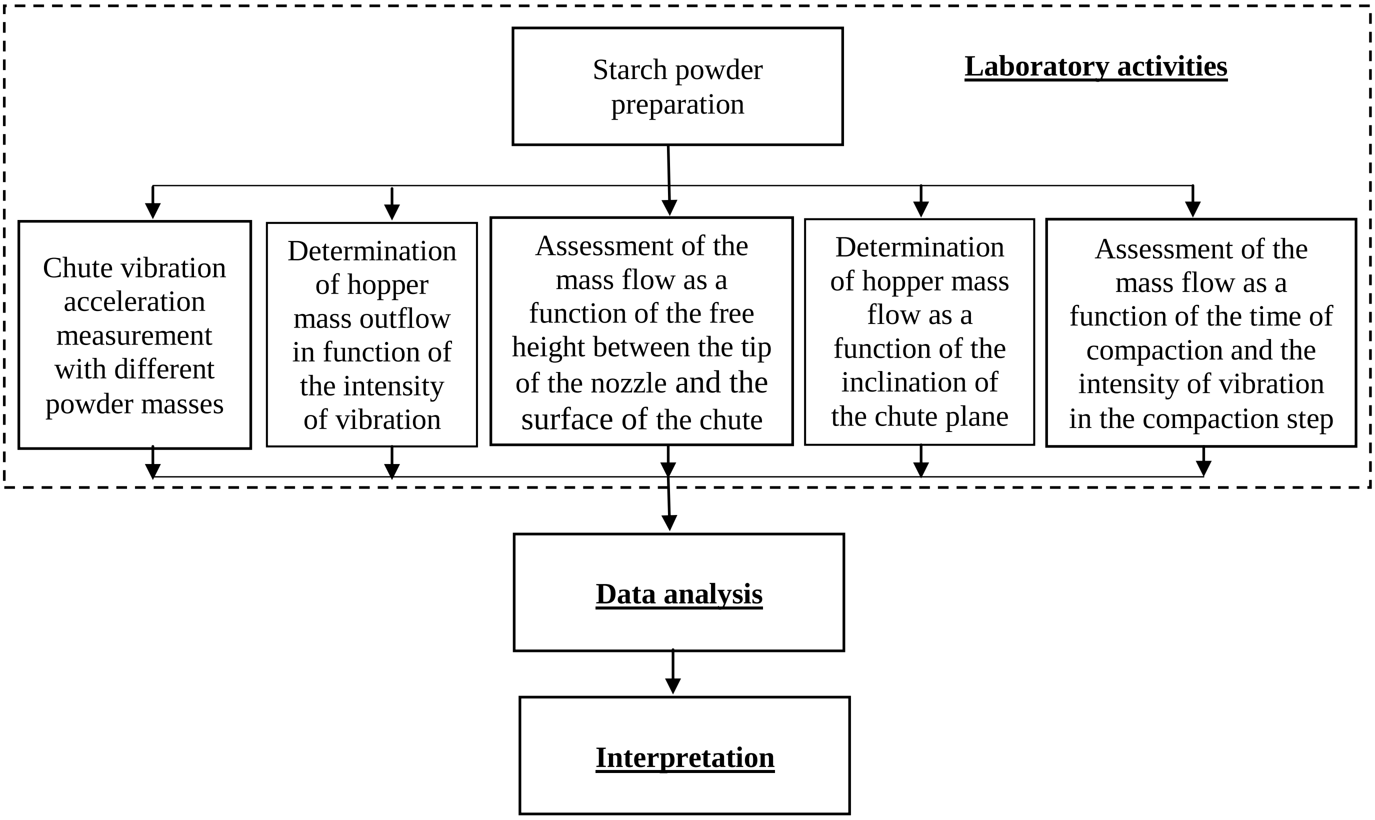



**Figure 21**. Project main activities

## *3.1* STARCH POWDER PREPARATION

Initially, starch powder had its original moisture content determined. Equipment model KERN 60 DBS 60-1 consists of an IR heating precision scale with dedicated software and it is to be used. This device is illustrated in the following Figure 22.


**Figure 22**. Equipment model KERN 60 DBS 60-1

Then, starch with different moisture levels was obtained by means of adding the objective amount of water to small amount of sample, storing under controlled temperature and shaking. The procedure comprises of:

- weighing 200 g of starch, measuring the level of moisture
- calculating the needed mass of water based on the original starch moisture level and the target
- spraying calculated additional mass of water
- adding material to individual sealed bags
- cooling materials at 8ºC for 15 days
- shaking materials 3 times/day

After this period the actual moisture level of the material each sealed in a bag was determined using the initial moisture determination procedure.

## *3.2* CHUTE VIBRATION ACCELERATION MEASUREMENT WITH DIFFERENT POWDER LOADS

This experiment comprised of measuring the vibration acceleration of the chute at masses of powder in the hopper in the range of zero up to 300 g, at 100 Hz, device generated vibration frequency, and with amplitude correspondent to different levels of the potentiometer controller, from 0 to 100% (0.05 to 6A).

The vibration acceleration measurements were processed by the Phyphox program run on a Samsung J5 smartphone accelerometer STM K2HH, range 4.0 g, resolution 0.001197 m.s$^{-1}$, sampling frequency of approximately 100 Hz. Once the sampling frequency of the accelerometer was close, but not equal to the vibration frequency (100 Hz), at each evaluated condition, samples were collected for 2 minutes, so that the maximum acceleration at each condition was registered.

Therefore, acceleration results were used to identify the influence of the hopper load on the frequency.

The procedure encompassed firstly installing the smartphone on the chute and open Phyphox. Then, close the outlet of the hopper, because when loading the respective mass, the mass flow from the outlet of the hopper along the chute is undesired; the parameter of interest was the acceleration registered in the Phyphox application, not the mass flow. Acceleration registers were proceeded in x, y and z axes, the first longitudinal to the chute, the second transversal to the chute and the third vertical, it means, perpendicular to x-y plane. The absolute acceleration was calculated based on the acceleration in the 3 axes by vectorial calculation, for this the z-axis acceleration was previously subtracted by gravity acceleration.

At this step, it is of particular importance to know the mass to be worked with and to fill into the hopper. In this experiment, four different masses of starch powder were compared: 0 g, 100 g, 200 g and 300 g. Smartphone and its fixations were considered to weight 200 g, When the respective powder mass was filled into the hopper and the vibration device was initiated, acceleration sampling started. Along the acceleration measurements, several steps of different intensity of vibration were done, being from 20% (0% and 10% are not considered because at these lower intensity values, acceleration measurements are not very accurate) to 100%. For this, the controller, which is shown in the Figure 23, was used.


**Figure 23**. Vibration controller

Thus, with the controller, and after 2 mins with the same intensity of vibration, 10% was increased for the same mass load until arriving at 100%. There were 9 steps of different intensities for four different masses loads, making a total of 36 steps. During the measurements, 10 seconds of delay were allowed for safety reasons and to stabilize the system. Figure 24 depicts the experimental set-up.

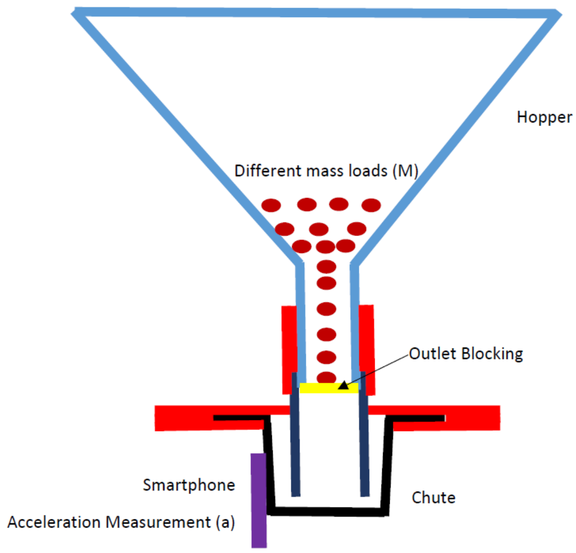



**Figure 24**. Powder load X Chute acceleration – Experimental set-up

*Observation: Room temperature, external RU%, external temperature, atmospheric pressure and powder moisture content of the material used were registered.*

## 3.3 DETERMINATION OF HOPPER MASS OUTFLOW AS A FUNCTION OF THE INTENSITY OF VIBRATION

For this procedure besides the integrated feeding system, a 0.01 g precision balance with automatic data logging was used connected to a computer to register the mass at instantaneous moments and to be able to calculate the mass flow. The procedure comprises of:

Powder loading and homogenizing (conditioning):

- Adjust free height tip outlet to chute surface at 10 mm

- Close hopper outlet
- Add 600 g of powder
- Vibrate for 30 seconds (controller at pre-defined level)
- Stop vibration, open outlet, collect material drop and gently reload the dropped material

Powder Flow (start up):

- Vibrate for 30 seconds (controller at 60%)
- Adjust the vibration level at the selected level
- Let material flow for 60 seconds at the selected intensity level
- Start balance registering
- Stop vibration device and balance registering when all material is conveyed

Then, it was repeated for different powder moisture levels (14%, 11% and 9%) and vibration intensities (controller) in order to find two comparisons at the same time. Figure 25 depicts the experimental scheme.

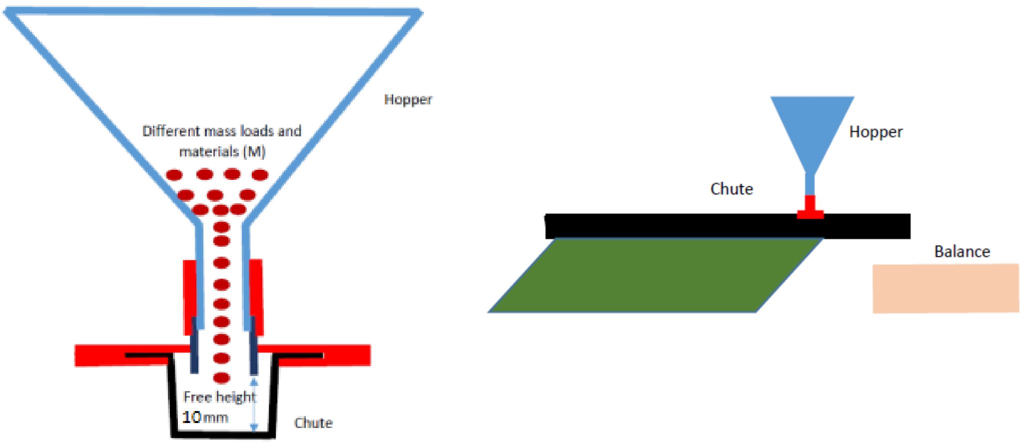



**Figure 25**. Powder load of starch at different moisture X Hopper mass flow – Experimental set-up

*<u>Observation</u>: Room temperature, external RU%, external temperature, atmospheric pressure and powder moisture content of the material used were registered.*

## *3.4* MASS FLOW ASSESSMENT WITH STARCH IN FUNCTION OF FREE HEIGHT

Also for this procedure, besides the integrated feeding system the 0.01 g precision balance with automatic logging data was used. The free height between the hopper tip outlet and chute surface was adjusted aiming to confine to mass flow of the hopper. The procedure comprehends:

Powder loading and homogenizing (conditioning):

- Adjust free height between the hopper tip outlet and chute surface at the desired value (7, 8, 9 and 10 mm)
- Close hopper outlet
- Add 600 g of powder
- Vibrate for 30 seconds (controller at predefined level)
- Stop vibration, open outlet, collect material drop and gently reload the dropped material

Powder Flow (start up):

- Vibrate for 30 seconds (controller at 60%)
- Adjust the vibration level at the selected level
- Let material flow for 60 seconds at the selected intensity level
- Start balance registering
- Stop vibration device and balance registering when all material is conveyed

Then, it was repeated for different powder moisture levels (14% and 9%), vibration intensities (controller) (35%, 37.5% and 40%) and free heights, in order to find several parameters' comparisons at the same time. Figure 26 depicts the experimental set-up.

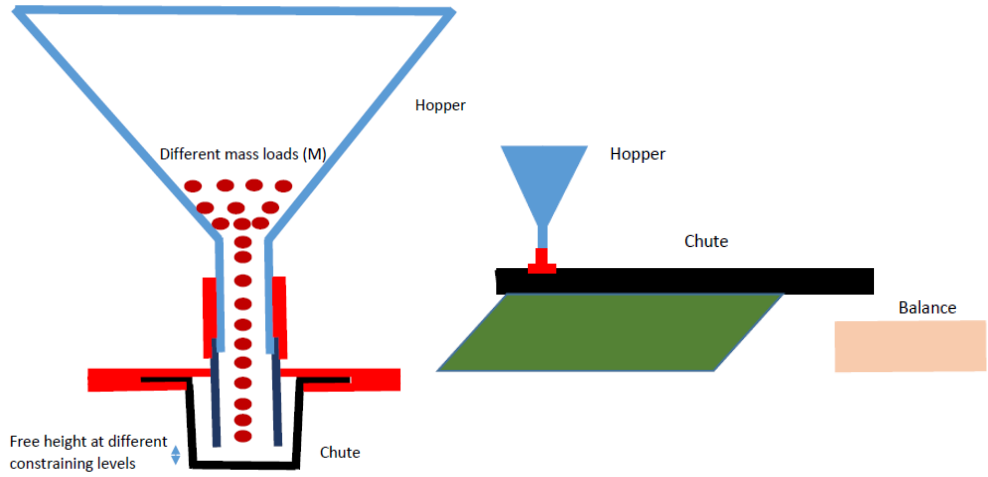



**Figure 26**. Powder load of starch at different moisture X System mass flow at different free heights – Experimental set-up

*Observation: Room temperature, external RU%, external temperature, atmospheric pressure and powder moisture content of the material used were registered.*

## 3.5 DETERMINATION OF HOPPER MASS FLOW AS A FUNCTION OF THE INCLINATION OF THE CHUTE PLANE

Also for this procedure, besides the integrated feeding system the 0.01 g precision balance with automatic logging data was necessary. The inclination of the chute surface was adjusted aiming to constraint to mass flow of the hopper. The procedure comprised of:

Powder loading and homogenizing (conditioning):

- Adjust inclination angle of the chute surface at the desired value (0%, 1% and 3.3% or 0%, 5.8% and 7.7% for different experiments)*multiple experiments lead to more results and then, more representative and easier to conclude
- Close hopper outlet

- Add 600 g of powder
- Vibrate for 30 seconds (controller at selected level)
- Stop vibration, open outlet, collect material drop and gently reload the dropped material

Powder Flow (start up):

- Vibrate for 30 seconds (controller at 80%)
- Adjust the vibration level at the selected level
- Let material flow for 60 seconds at the selected intensity level
- Start balance registering
- Stop vibration device and balance registering when all material is conveyed

Then, it was repeated for different powder moisture levels (14% and 12%), vibration intensities (controller) (40% and 42.5%), in order to find several parameters' comparisons at the same time. The experiment can be modeled as one of the figures presented before, but taking into account that here the angle of inclination of the chute surface is going to vary. This was achieved by inclining and supporting the entire equipment, i.e., chute and case at defined levels.

*Observation: Room temperature, external RU%, external temperature, atmospheric pressure and powder moisture content of the material used were registered.*

## 3.6 MASS FLOW ASSESSMENT AS A FUNCTION OF MATERIAL CONDITIONING IN THE HOPPER

Also for this procedure, besides the integrated feeding system the 0.01 g precision balance with automatic logging data was used. The procedure comprehended different steps depending on whether the study parameter was the time of compaction or the intensity of vibration in the compaction step.

The operational steps to evaluate the effects of time in material conditioning in hopper were:

Powder loading and homogenizing (conditioning):

- Adjust free height tip outlet to chute surface at 10 mm
- Close hopper outlet
- Add 600 g of powder
- Wait until the selected time duration lapsed during which the compaction is taking place
- Open outlet

Powder Flow (start up):

- Vibrate for 30 seconds (controller at 60%)
- Adjust the vibration level at the selected level
- Let material flow for 60 seconds at the selected intensity level (40% in this case)
- Start balance registering
- Stop vibration device and balance registering when all material is conveyed

*<u>Observation</u>: Room temperature, external RU%, external temperature, atmospheric pressure and powder moisture content of the material used were registered.*

The operational steps to evaluate the effects of vibration in material conditioning in the hopper were:

Powder loading and homogenizing (conditioning):

- Adjust free height tip outlet to chute surface at 10 mm
- Close hopper outlet
- Add 600 g of powder

- Vibrate for 30 seconds (controller at the selected intensity of vibration during compaction)
- Stop vibration, open outlet, collect material drop and gently reload the dropped material

Powder Flow (start up):

- Vibrate for 30 seconds (controller at 60%)
- Adjust the vibration level at the selected level
- Let material flow for 60 seconds at the selected intensity level
- Start balance registering
- Stop vibration device and balance registering when all material is conveyed

*Observation: Room temperature, external RU%, external temperature, atmospheric pressure and powder moisture content of the material used were registered.*

# 4. RESULTS AND DISCUSSION

## *4.1* EVALUATION OF THE EFFECT OF THE AMOUNT OF POWDER IN THE HOPPER ON THE VIBRATION ACCELERATION AT THE CHUTE

The results after applying the techniques described in subsection *3.2* CHUTE VIBRATION ACCELERATION MEASUREMENT WITH DIFFERENT POWDER LOADS, as well as a discussion of the results, are presented below.

**Initially, the effect of the intensity of vibration is presented set at the controller on the acceleration of the three x, y and z-axes, for different mass loads.**

The figures 27, 28 and 29 show the variation of the acceleration when increasing the intensity of vibration in the controller, in the three spatial x, y and z-axes, respectively for different mass loads.

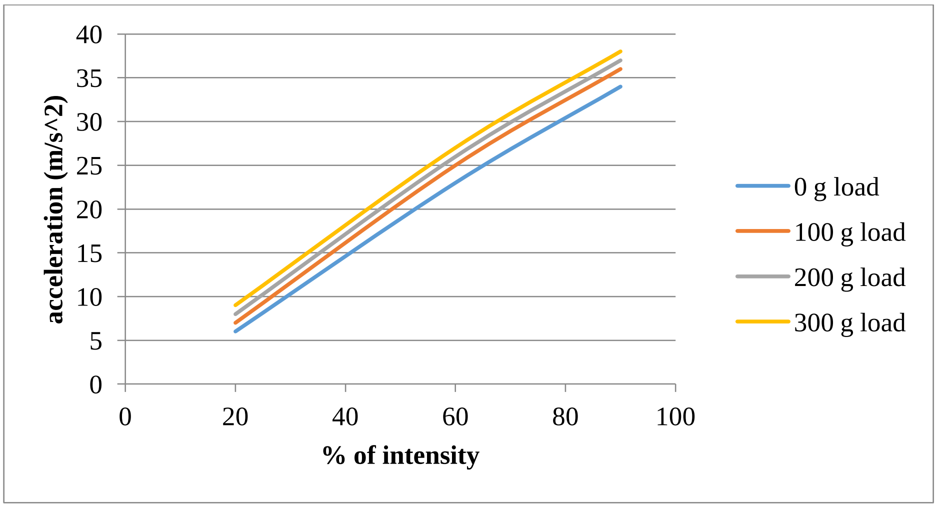



**Figure 27**. Influence of the intensity in the x-axis acceleration for different mass loads

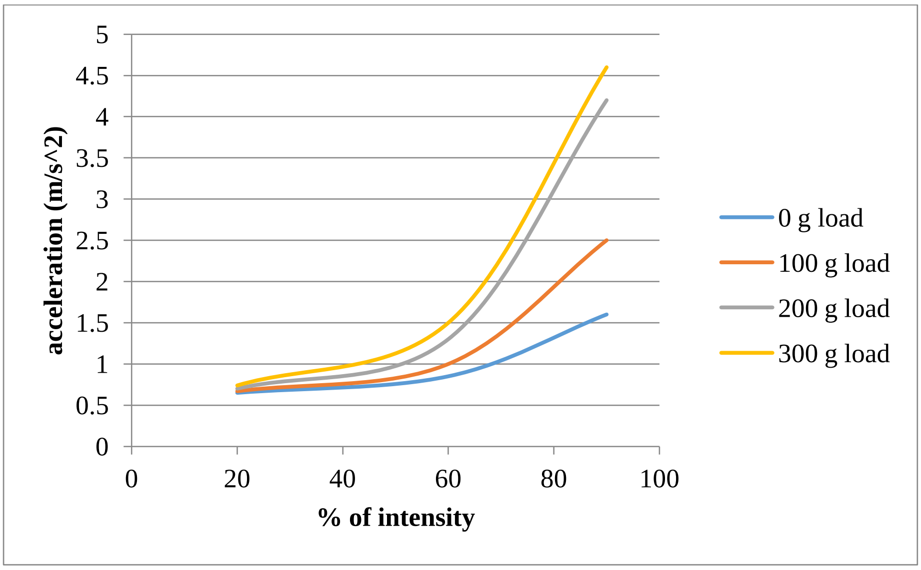



**Figure 28**. Influence of the intensity in the y-axis acceleration for different mass loads

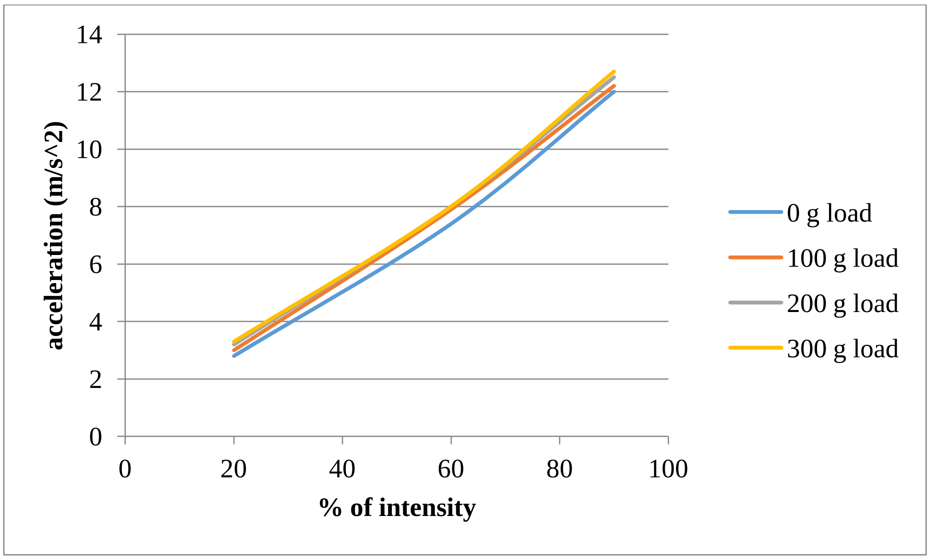



**Figure 29**. Influence of the intensity in the z-axis acceleration for different mass loads

*<u>Observation</u>: Room temperature: 22.3ºC; external RU%: 60%; external temperature: 7.9ºC; atmospheric pressure: 969.1 hPa; and powder moisture content of the material used: 9%.*

From this analysis, it can be seen that the acceleration in the case of all space axes, increases with the intensity of vibration adjusted in the controller. The x-axis is longitudinal to the chute and the z-axis is vertical. An increase in the acceleration in these axes is related to an increase in the transportation capacity of the chute, according to the principle of functioning of EMVFs. The adjustment between 0 to 100% intensity is respective to an increase from 0.05 to 6A in the potentiometer, this explains the almost linear increase in directions x and z. Comparatively, the acceleration in y-axis is much smaller than in x and z. For a vibration intensity of 90%, the y-axis presents a range of accelerations between 1.6 $m/s^2$ and 4.6 $m/s^2$ depending on the mass loaded. These values are much lower than those of the x-axis and z-axis for the same vibration intensity, which are between 34 $m/s^2$ and 38 $m/s^2$ and 12 $m/s^2$ and 12.7 $m/s^2$, respectively. The y-axis is transversal to the chute; an increase of vibration in this axis is not intentional for increase in the transport capacity. Moreover, there is a relation of the mass load in the hopper and the acceleration studied; a higher material mass loaded in the hopper is translated by an increase in the acceleration. The curve corresponding to 300 g of material loaded is in the three cases situated above the other curves, contrary to the situation when no material is loaded, whose curve is situated below them. The device was tuned to vibrate at a frequency closer to the natural one. If the mass is reduced, the natural frequency of the vibrating object increases and distances further from the drive frequency which remains the same, leading to a reduction of the vibration amplitude. Therefore, when the load gets more distant to the weight that the system was tuned for, acceleration reduces.

**The influence of the mass load on the absolute acceleration for different intensities of vibration was assessed.**

Figure 30 represents the percent of reduction of the acceleration for three series of mass consumption (100 g, 200 g and 300 g) depending on some vibration intensities taken for the analysis. Thus, the basis acceleration corresponds to the situation when the working weight is 2500 g, which corresponds to 2000 g of the vibrating set, plus 200 g of the smartphone used for the analysis and 300 g of the powder within the hopper. Thus, the variation of the acceleration for a consumption of 100 g corresponds to a situation when the working weight is 2400 g.

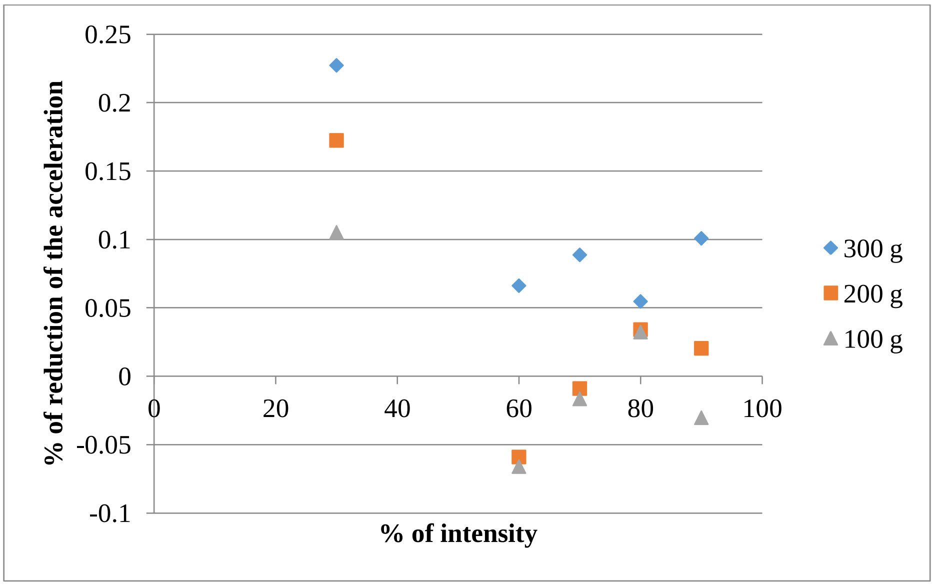



**Figure 30**. Negative acceleration reduction for different mass consumption depending on the vibration intensity (initial ww = 2500g)

The percent of reduction of the acceleration from the basis acceleration with 2500 g of working weight, is higher for the case of 300 g of consumption, i.e., when 0 g of powder are in the hopper. This supports the above mentioned; if the mass reduces 300 g, the natural frequency of the vibrating object increases and distances further from the drive frequency which remains the same, leading to a reduction of the vibration amplitude and acceleration, and consequently to an increase of the % of reduction from the basis acceleration.

It is noticed that there seems to be some data scatter. It is likely to think that it may be due to the selection of experimental parameters that are not so suitable for the experiment. This experiment was carried out at the beginning so material behavior depending on the experimental parameters was not so known. The choice of parameters that were not entirely appropriate could have led to the formation of irregularities as for example blocks in the flow, etc, that could lead to some results less representative.

Nevertheless, it is interesting to analyse also in terms of the mass flow, which will be the parameter evaluated in the next experiments. As it has been proved before, with a higher acceleration, higher is the mass flow. Another experiment, where mass flow is the parameter measured, has been carried out, arriving at the Figure 31.

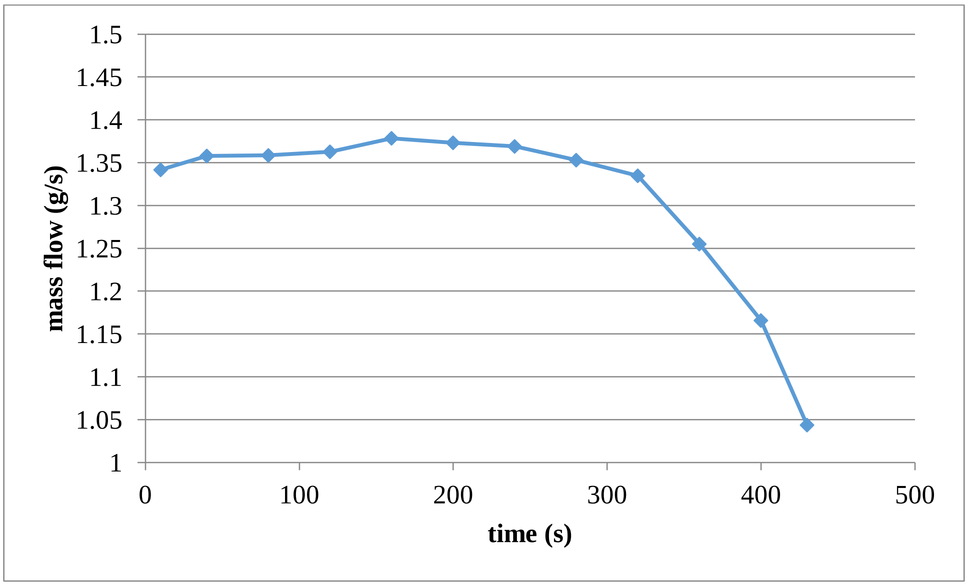



**Figure 31**. Variation of the mass flow along the time for a 9% moisture material, 10 mm of free height between the tip of the nozzle and the surface of the chute, 40% of intensity of vibration and 4% of inclination of the plane

In Figure 31, the behaviour of the mass flow over time is clearly visible, presenting a slight increase at the beginning up to a maximum around an intermediate time value, i.e., an intermediate mass, and followed by a decrease at approximately 240 s, correspondent to a mass of 271 g in the hopper, having already discharged 329 g of the initial 600 g out of the system during that time with an average flow rate of 1.37 g/s. The increase in difference from the drive frequency to the natural frequency has a reduction in the acceleration as a consequence. Therefore a decrease is observed in the transportation capacity of the system, according to the principle of functioning of EMVFs mentioned above. Due to gravity, the self weight of powder pushes down on particles below in the nozzle, so powder at the bottom of the hopper experiences the highest compaction stress, leading to the initial slight increase of the mass flow in Figure 31.

## *4.2* EVALUATION OF THE INFLUENCE OF THE VIBRATION INTENSITY ON THE MASS FLOW CONTROL

In the following, the results after applying the techniques described in subsection *3.3* DETERMINATION OF HOPPER MASS OUTFLOW IN FUNCTION OF THE

INTENSITY OF VIBRATION, as well as a discussion of the results, are presented below.

### Influence of the vibration intensity on the mass flow control

Figures 32, 33 and 34 show the relation between the mass flow and the intensity of vibration of the controller for a 14%, 11% and 9% moisture content material, respectively.

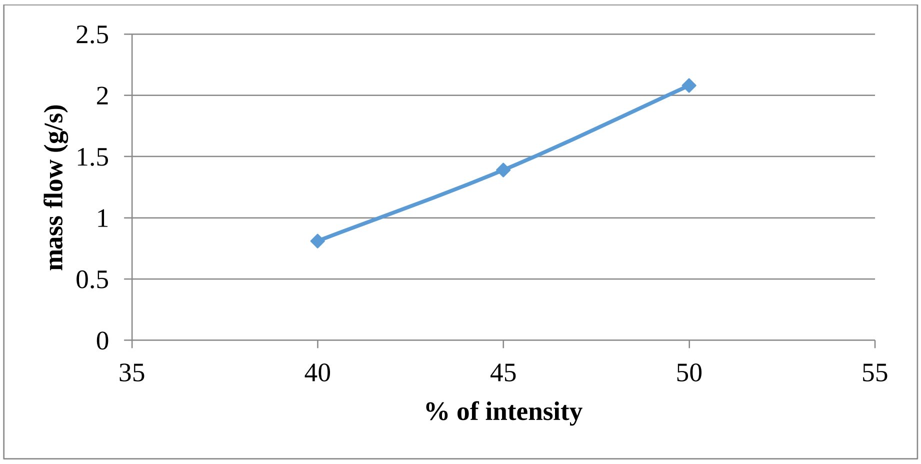



**Figure 32**. Variation of the mass flow depending on the intensity of vibration for a 14% moisture material. Invariable experimental parameters: moisture content = 14%, height between the tip of the hopper and the chute = 18 mm, inclination level of the plane = 0%.

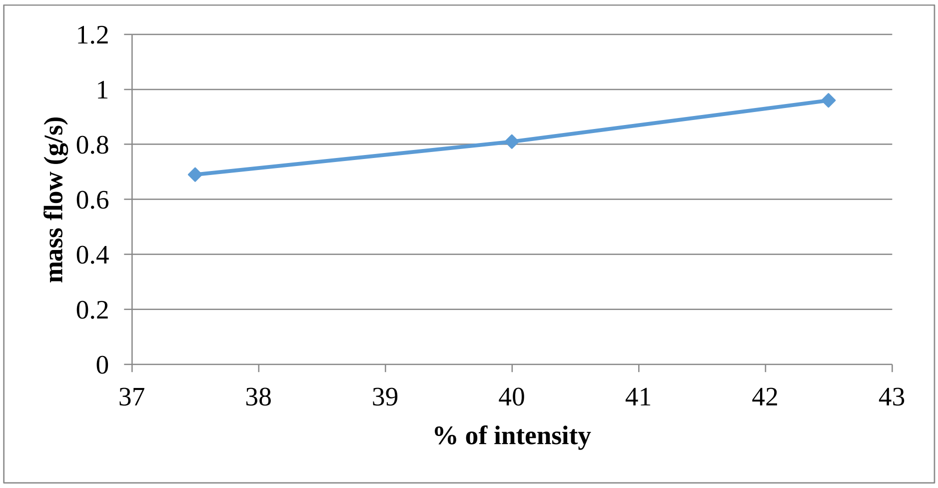



**Figure 33**. Variation of the mass flow depending on the intensity of vibration for a 11% moisture material. Invariable experimental parameters: moisture content = 11%, height between the tip of the hopper and the chute = 10 mm, inclination level of the plane = 0%.

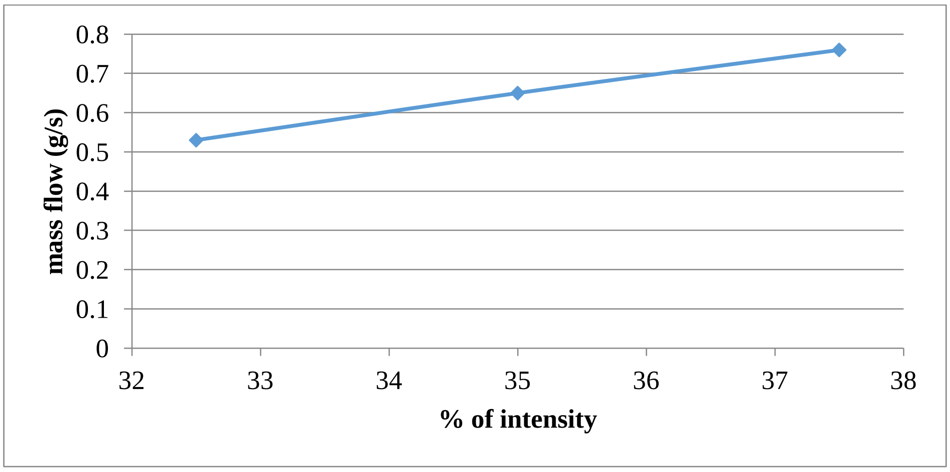



**Figure 34**. Variation of the mass flow depending on the intensity of vibration for a 9% moisture material. Invariable experimental parameters: moisture content = 9%, height between the tip of the hopper and the chute = 8 mm, inclination level of the plane = 7.7%.

*<u>Observation</u>: Room temperature: 22.1ºC; external RU%: 71%; external temperature: 13.8ºC; atmospheric pressure: 968.6 hPa; and powder moisture content of the material used: 14% / 11% / 9%.*

The effect of the intensity of vibration on the mass flow can also be seen at different heights between the tip of the hopper and the chute in Figure 35.

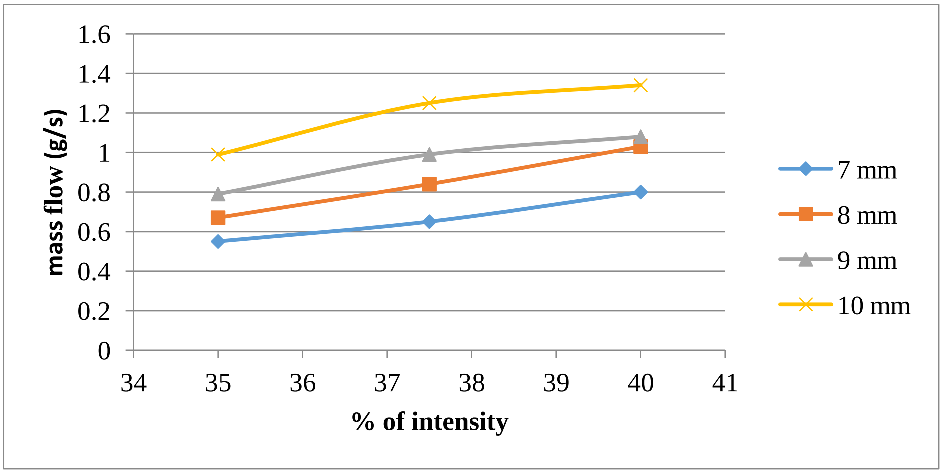



**Figure 35**. Variation of the mass flow depending on the intensity of vibration for a 9% moisture material and different heights between the tip of the hopper and the chute. Invariable experimental parameters: moisture content = 9%, heights between the tip of the hopper and the chute = 7, 8, 9 and 10 mm, inclination level of the plane = 4%.

From these analyses, it is clear that the mass flow depends on the intensity of vibration. When the latter increases, so does the mass flow. The vibration generates a shear field and, as a result, adhesion forces between particles are overcome by forces generated in the shear field; particles lose contact and flow easier by the powder pressure under gravity. Lower intensities applied to the experimental conditions and materials above resulted in a nozzle outlet blockage, characterizing a mass flow limit for the experimental conditions. In these cases, the vibration intensity was too low to reduce the shear strength between the particles and to cause the separation among them. This limitation was intensified in the nozzle due to its narrower diameter which gathered the particles together, causing the outlet blockage mentioned above. Material was not able to flow at the chosen conditions, and therefore, the mass flow measurement was not possible. This made the determination of a critical acceleration necessary, which constituted of the minimal vibration intensity needed to make the material flow at the chosen conditions and which was taken into account for a possible flow in the following experiments.

## *4.3* EVALUATION OF THE EFFECT OF THE INCLINATION OF THE CHUTE SURFACE ON THE MASS OUTFLOW

In the following, the results after applying the techniques described in subsection *3.5* DETERMINATION OF HOPPER MASS FLOW IN FUNCTION OF THE INCLINATION OF THE CHUTE PLANE, are presented below.

### Effect of the inclination of the chute on the mass flow control

Figures 36 and 37 show the relation between the mass flow and the inclination of the plane for different moisture contents material.

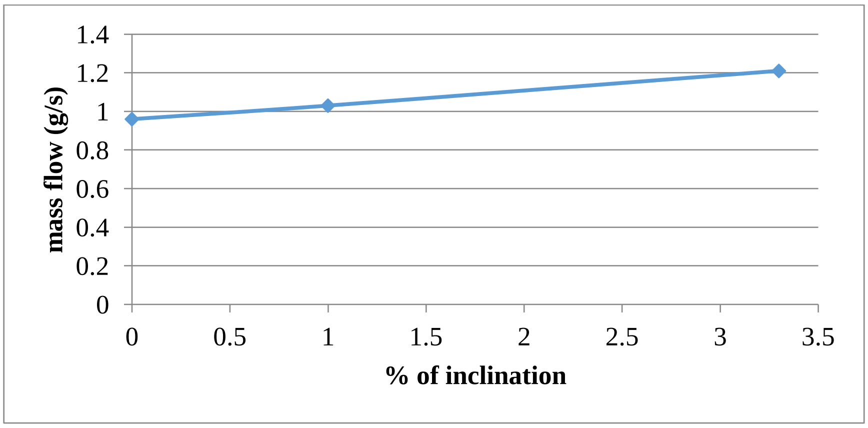



**Figure 36**. Variation of the mass flow depending on the inclination of the plane for a 12% moisture material. Invariable experimental parameters: moisture content = 12%, heights between the tip of the hopper and the chute = 9 mm, intensity of vibration = 42.5%.

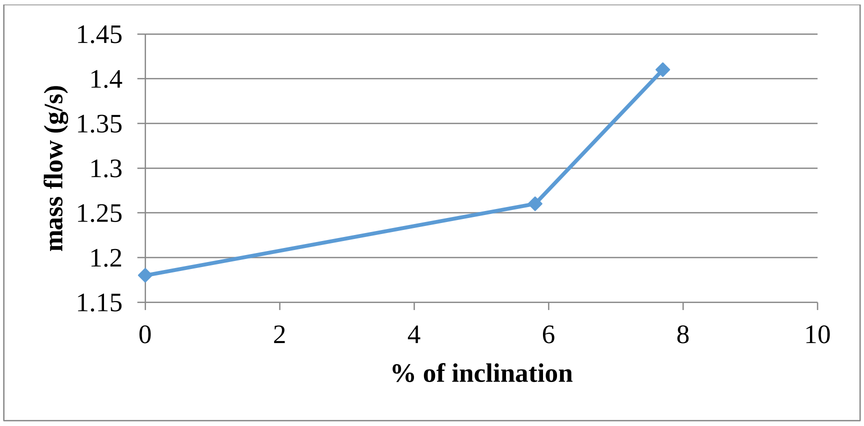



**Figure 37**. Variation of the mass flow according to the inclination of the plane for a 14% moisture material. Invariable experimental parameters: moisture content = 14%, heights between the tip of the hopper and the chute = 14 mm, intensity of vibration = 40%.

*<u>Observation</u>: Room temperature: 21ºC; external RU%: 68%, external temperature: 4.6ºC, atmospheric pressure: 977.9 hPa; and powder moisture content of the material used: 14% / 12%.*

From these analyses, a clear influence of the inclination of the plane is observed on the mass flow; when the inclination increases, so does the mass flow. The used integrated system could be understood as a two-step process through which material is fed. The flow through the hopper and subsequently the chute. As per the TOC, the overall mass flow will be given by the step of lower capacity, which constitutes of the hopper for a given adjustment of nozzle height and vibration intensity. This is true as long as the chute does not overflow the conveyed material and the material does stay on the chute surface blocking the subsequent flow and representing a severe constraint. The application of a positive inclination to the system leads to an increase of the material velocity at the outlet of the nozzle. Therefore, by a positive inclination, there is a reduction of the hopper constraint and, consequently, the mass flow of the system increases.

## *4.4* ASSESSMENT OF THE INFLUENCE OF THE FREE HEIGHT BETWEEN THE TIP OF THE NOZZLE AND THE SURFACE OF THE CHUTE ON THE MASS FLOW

In the following, the results after applying the techniques described in subsection *3.4* MASS FLOW ASSESSMENT WITH STARCH IN FUNCTION OF FREE HEIGHT, as well as a discussion of the results, are presented below.

### Influence of the height on the mass flow control

Figure 38 shows the relation between the mass flow and the height between the hopper and the chute.

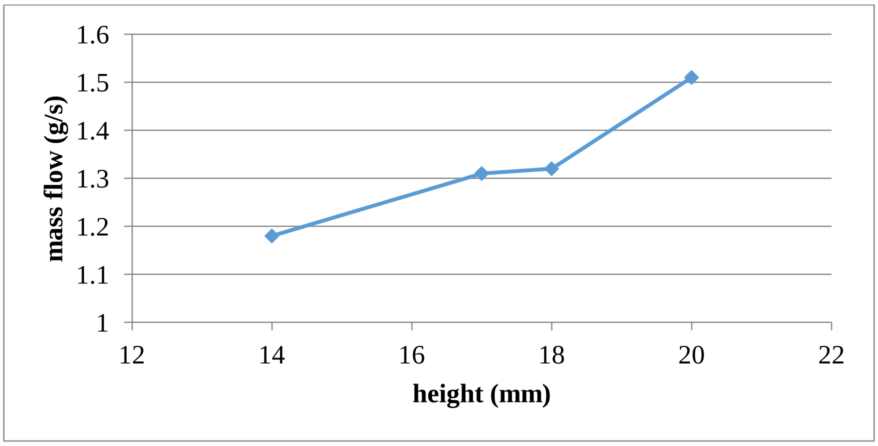



**Figure 38**. Variation of the mass flow depending on the height between the hopper and the chute for a 14% moisture material. Invariable experimental parameters: moisture content = 14%, inclination of the plane = 0%, intensity of vibration = 40%.

In addition, Figure 39 shows the effect of the height on the mass flow at different intensities of vibration.

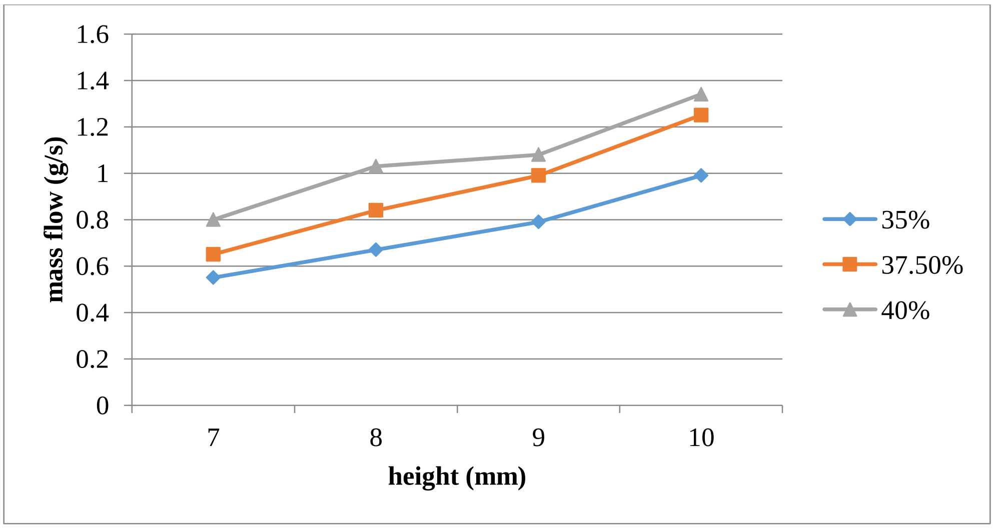



**Figure 39**. Variation of the mass flow depending on the height between the hopper and the chute for a 9% moisture material and different intensities of vibration. Invariable experimental parameters: moisture content = 9%, inclination of the plane = 4%, intensity of vibration = 35, 37.5 and 40%.

*Observation: Room temperature: 20ºC; external RU%: 73%; external temperature: 2.6ºC, atmospheric pressure: 978.9 hPa; and powder moisture content of the material used: 14% / 9%.*

From these analyses, it is clear that the mass flow depends on the height between the tip of the hopper and the chute. When the latter increases, so does the mass flow. As stated before, the flow through the hopper constitutes the constraint step among the two steps that form the system (flow through hopper and through chute), due to the fact that, as per the TOC, it determines the overall mass flow because of its lower capacity. Increasing the height between the tip of the hopper does not change the conveying capacity of the chute, but it has an influence of the flow through the hopper. Thus, the outflow of the hopper is eased and the constraint optimized, leading to a higher velocity at the outlet of the nozzle. Therefore, by a higher height, there is a reduction of the hopper constraint and, consequently, the mass flow of the system increases. At the experimental conditions and materials above, at heights smaller than the ones presented, blockage of nozzle outlet occurred. When reducing the height between the tip of the hopper and the chute, the outlet space for the exit of the material from the nozzle is reduced. This represents an increase in the constraint, so a reduction of mass flow, thus a reduction of velocity of the material through the outlet. At a certain point, if material velocity is too low, the applied vibration intensity can be insufficient to generate enough shear field to overcome cohesion and adhesion forces, leading to blocking.

It is also interesting to look to Figure 39, in which both influencing parameters, intensity and the height, can be observed on mass flow. As it has been studied previously, the influence of the intensity of vibration is also significant; the curve in the situation of highest intensity is above the others, and the contrary occurs with the case of lowest intensity, whose curve is situated at the bottom. Thus, it can be deduced that with higher vibration intensity, a higher mass flow is achieved in the system, as it has already been proven.

## *4.5* EVALUATION OF THE EFFECT OF THE COMPACTION (TIME AND INTENSITY OF VIBRATION) IN THE HOPPER ON THE MASS FLOW

In the following, the results after applying the techniques described in subsection *3.6* MASS FLOW ASSESSMENT AS A FUNCTION OF THE TIME OF COMPACTION AND THE INTENSITY OF VIBRATION IN THE COMPACTION STEP, as well as a discussion of the results, are presented below.

### Compaction effect on the mass outflow

Figure 40 shows some of the data obtained when evaluating both time and intensity of compaction in the hopper; when the rest time is 3 min and 7 min, and the intensity of compaction of 30% and 80% during 30 seconds.

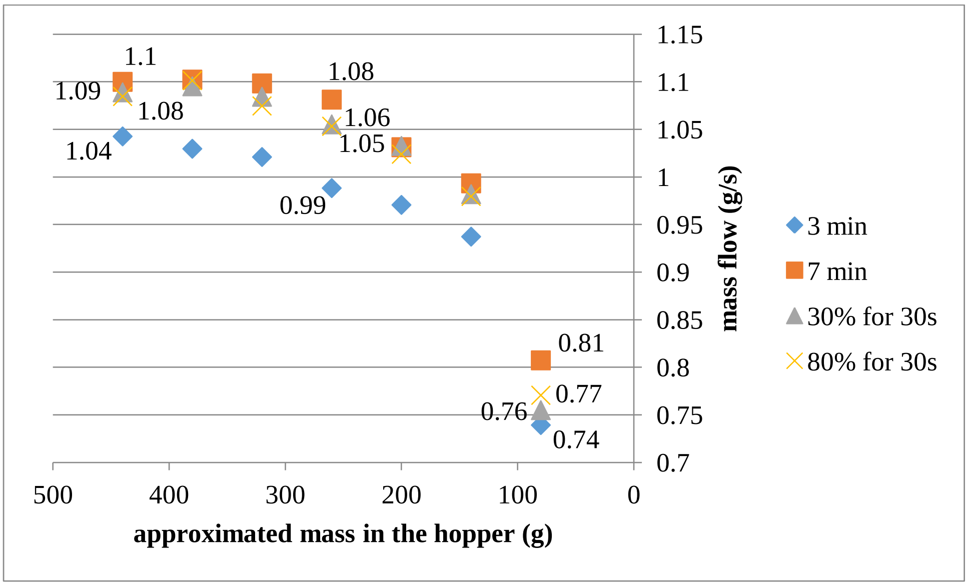



**Figure 40**. Mass flow depending on the mass approximated in the hopper for different compaction conditions

*<u>Observation</u>: Room temperature: 21ºC; external RU%: 80%; external temperature: 5.8ºC; atmospheric pressure: 979.7 hPa; and powder moisture content of the material used: 8%.*

It is interesting to note that in Figure 40, this way of representing the mass flow over the approximated mass in the hopper as an inverse axis that goes from 500 left to zero right is just a matter of vision. This decreasing behavior of the mass flow can also be seen in Figure 31, but considering the evolution of the time in the x-axis. Therefore representing in Figure 40 the mass into the hopper in descending order was analogous to a graphical representation over time, due to the decrease of the mass within the hopper along the experiment. It served to check the mass flow behavior previously demonstrated.

Moreover, from Figure 40, a clear effect of the time of compaction can be observed; when increasing the time of compaction from 3 min to 7 min, the mass flow increases too given that the same powder mass is in the hopper. In the case of peak values, when conditioning the material for 3 min a mass flow of 1.04 g/s was noticed, while increasing conditioning for 7 min mass flow increased for 1.1 g/s. From the initial moment powders are filled, they may increase their internal strength (also known as "failure strength"). Due to gravity, the self weight of powder pushes down on particles below and air gradually squeezes out from empty spaces between particles. Consolidation takes place as particles move closer together. Increases in powder strength between the particles depend on the amount of time the powder remains stationary and undisturbed. More time the powder remains stationary, more the particles accommodate each other increasing the strength between them and leading to an increase of the mass flow.

However, it is not the same in the case of the increase in the intensity of vibration. Effectively, there is no clear influence while increasing intensity of vibration from 30% to 80% for 30 seconds. Maybe this could be due to the fact that the tested 30 seconds time of compaction is not sufficient to make a clear difference in the results. If this was the case, it is likely to think that a longer time with these two chosen intensities could probably make a difference in the mass flow.

## *4.6* ASSESSMENT OF THE EFFECT OF THE MOISTURE CONTENT ON THE MASS OUTFLOW

Several runs with different % of moisture content were made and the results were analyzed. The results, as well as a discussion of them, are presented below.

### Effect of the content of moisture on the mass flow

Figure 41 shows the influence of the content of moisture on the mass flow.

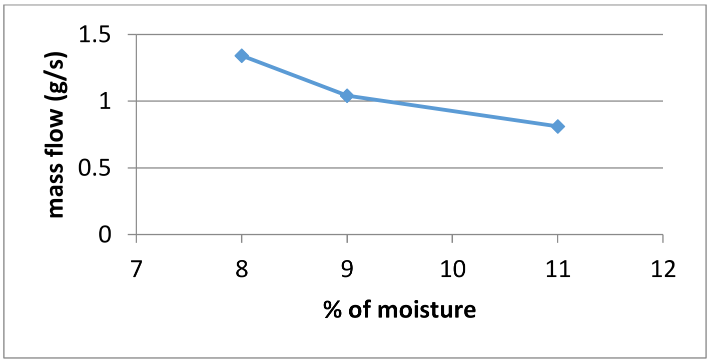



**Figure 41.**Variation of the mass flow depending on the moisture content. Invariable experimental parameters: Height between the tip of the hopper and the surface of the chute = 10 mm, inclination of the plane = 0%, intensity of vibration = 40%.

The decreasing curve in Figure 41 shows effectively the influence of the content of moisture in the mass flow; when the moisture increases, the mass flow decreases. In other words, the higher the content of moisture is, the more difficult it is for the material to flow. When the moisture content is low, it is initially adsorbed on the particle surface affecting the flowability of particles favorably. However, when the moisture content increases, high cohesive forces among particles are formed causing the pellicular water on the periphery of adsorbed water to reduce further the flowability of particles. Finally, with further more moisture content, capillary water forms on the surface of particles, leading to a higher reduction of the free flowability of particles.

## 5. CONCLUSIONS

The vibrating chute integrated to a simple hopper had the main control parameters identified and assessed for starch powder at different moisture levels, so different flowabilities, the conclusions are drawn as follows:

- **Effect of the moisture content on the mass flow**. The moisture content (8% to 14%) has proved to be one important parameter of the material to take into account due to its influence on the mass flow results. A higher content of moisture of the sample results in a decrease in the mass flow. In other words, an increase in the moisture worsens the flowability. This means that for a better flowability, it will be sought to work with lower moisture content material. Surface phenomena involving pellicular water and capillary are responsible for the cohesion and effect on material flowability.

- **Effect of the free height on the mass flow**. Mass flow and free height are directly proportional in the evaluated range; when free height between the tip of the nozzle and the chute increases, so does the mass flow. Then, for a given vibration intensity and material, setting greater free height, always within appropriate limits, is going to be of special interest in order to achieve a higher mass flow. In the other way, at a given vibration intensity, setting smaller free height will produce lower mass flow, and limitation of the system can be found by nozzle outlet blocking. In the studied integrated set, the free height limits the constraint process step, the flow through the hopper.

- **Effect of the intensity of vibration on the mass flow**. In the evaluated conditions mass flow was shown to be directly proportional to the intensity of vibration set at the controller; when increasing the intensity of vibration, so will be the vibration acceleration and consequently the mass flow. For a given free height and material, the lower feasible mass flow will be achieved by reducing the vibration intensity close to the one that generates blocking while operating. The intensity of vibration influences the shear field that goes against the cohesion and adhesion forces within material particles.

- **Influence of the inclination of the plane on the mass flow**. The application of a positive inclination to the system leads to an increase of the material velocity at the outlet of the nozzle. The outflow of the hopper is eased and the hopper constraint reduced, leading to an increase of the mass flow.

- **Influence of the mass load in the hopper on the vibration acceleration and on the mass flow**. When reducing the mass load, the natural frequency of the vibrating object increases and distances further from the drive frequency which remains the same. This leads to a reduction in the acceleration, therefore a decrease in the mass flow after an initial stable zone, which is characterized by the highest compaction stress suffered by the particles in the nozzle due to their self weight that pushes them down.

- **Influence of the time and the intensity of vibration used during conditioning**. The change of intensity of vibration from 30% to 80% in 30 s period used during conditioning step did not influence the mass flow. However, the time of compaction from 3 to 7 minutes led to a higher mass flow. Due to gravity, the self weight of powder pushes down on particles below and air gradually squeezes out from empty spaces between particles. These latter present an increase of the powder strength between them, leading to an increase of the mass flow, which is enhanced with more time of compaction.

## *5.1* PROPOSALS FOR THE FUTURE

On the basis of this study, different new work fronts that open up are manifold. By way of example, the following is a list of some of them:

- Work with other types of material (here, only one type of starch was used), in order to learn about the behavior of other materials with different characteristics.

- Understand the effect of the mass loading step and look for its effects in mass flow. As it has been proven in this study, that the amount of mass loaded influences the acceleration and thus the mass flow. With this latter, it may be relevant to investigate a way of loading to achieve a defined final mass flow.

- This study was conducted for batches and a stable mass flow zone was identified up to a certain amount of material consumption. Investigating periodical hopper refill of material within the stable mass flow zone and their effects on mass flow would bring understanding for a semi-continuous process design.

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# *Annexes*

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# 1. ANNEXE 1: EFFECT OF NUMEROUS RUNS ON THE MATERIAL MOISTURE

## *1.1* EFFECT ON 15% MOISTURE MATERIAL

Between some experiments, the moisture content of the starch material was sometimes measured in order to ensure that the moisture content of the material to be worked with was as expected. However, it was noticeable that the moisture content of the material was decreasing along the experiments. That is why it was decided to do successive experiments with the same sample in order to verify that this phenomenon was true. Table 1 summarizes the results of the percent of moisture obtained in an experiment with four bags of 600 g of sample of the same material each bag: MSH13-3,4,11, MSH13-8,9,12, MSH13-1,2,5 and MSH13-6,7,10 (around 15%).

| Material | % moisture | Run | % of vibration at the run | Observations |
|---|---|---|---|---|
| MSH13-3,4,11 | 15.7% | 1 | 50% 70%-75% | 12mm. 0 inclination. |
| MSH13-3,4,11 | 15.3% | 2 | 50%-55% | 14mm. 0 inclination. |
| MSH13-3,4,11 | 14.9% | 3 | 50%-55% 45% | 14mm. 7,7% inclination = Below 3g/2s. |
| MSH13-3,4,11 | 14.7% | 4 | 40% | 14mm. 7,7% inclination --> 2 blocking |
| MSH13-3,4,11 | 14.3% | 5 | 40% | 14mm. 0 inclination --> 1 blocking, FINAL MOISTURE: 14% |
| MSH13-8,9,12 | 15.6% | 1 | 45% | 10mm. 0 inclination. |
| MSH13-8,9,12 | - | 2 | 60% | 15mm. 0 inclination. |
| MSH13-8,9,12 | - | 3 | 50% | 18mm. 0 inclination. |
| MSH13-8,9,12 | 14.5% | 4 | 45% | 18mm. 0 inclination. |
| MSH13-1,2,5 | 15.6% | 1 | 45% | 18mm. 0 inclination. Blocked x3 |
| MSH13-1,2,5 | - | 2 | 45% | 18mm. 0 inclination. 1 block |
| MSH13-1,2,5 | - | 3 | 40% | 18mm. 0 inclination. |
| MSH13-1,2,5 | 14.3% | 4 | 40% | 17mm. 0 inclination. |
| MSH13-6,7,10 | 15.6% | 1 | 40% | 17mm. 0 inclination. |
| MSH13-6,7,10 | - | 2 | 40% | 17mm. 0 inclination. |
| MSH13-6,7,10 | - | 3 | 50% | 17mm. 0 inclination. 1 block. |
| MSH13-6,7,10 | 14.8% | 4 | 40% | 16mm. 0 inclination. |

**Table 1**. Experiment looking for the change in the moisture content of MSH13-3,4,11, MSH13-8,9,12, MSH13-1,2,5 and MSH13-6,7,10 (around 15%)

The moisture content was measured before the run in some cases; it decreases approx 0.4% after each run. Therefore, from Table 1, this phenomenon is clearly documented: The moisture content decreases along different runs when using the same sample of material.

## *1.2* EFFECT ON 13.50% MOISTURE MATERIAL

The same is proven by Table 2 for the same sample of MSH6,7,8,9,10 (around 13.50%).

| Material | % moisture | Run | % of vibration at the run | Observations |
|---|---|---|---|---|
| MSH6 to 10 | 14.20% | 1 | 40% | Blocked at 20s. 16mm. |
| MSH6 to 10 | | 2 | 45% | Blocked again. 16mm. |
| MSH6 to 10 | | 3 | 50% | 16mm. |
| MSH6 to 10 | | 4 | 40% | 18mm. |
| MSH6 to 10 | 13.50% | 5 | 45% | 18mm. |
| MSH6 to 10 | | 6 | 50% | 18mm. |
| MSH6 to 10 | | 7 | 40% | 20mm. |
| MSH6 to 10 | | 8 | 45% | 20mm. |
| MSH6 to 10 | 12.80% | 9 | 50% | 20mm. |

**Table 2**. Experiment looking for the change in the moisture content of MSH6,7,8,9,10 (around 13.50%)

In this case, the moisture decreases also but more slowly, in a: (14.20-13.50)/5 = 0.14%, significantly lower to 0.4% of reduction in the previous case. Then, it makes sense to ask why the moisture content varies more in the first case (around 15%) than in this one (around 13.50%). A possible explanation may be that a higher moisture is translated by a higher gradient (higher difference) between the moisture in the material and the one in the environment. This higher gradient leads to a higher tendency of the water to be transferred to the environment, and then, to a faster reduction of the moisture content of the material.

## *1.3* REASONS FOR THIS EFFECT

Concerning this phenomenon of drying, there should be a physically sound explanation for what occurs during the run. Indeed, when flowing on the chute during the run, the particles suffer friction with solid surfaces as well as with each other due to their flowing movement. The friction is defined as the resistance to motion of one object moving relative to another, and can be schematized as Figure 1.

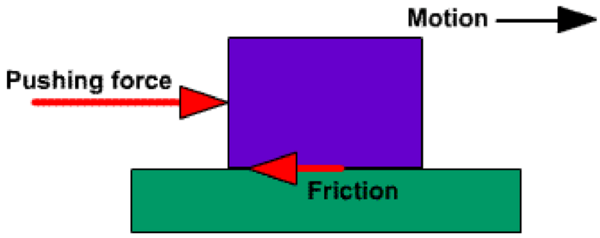


**Figure 1**. The process of friction

*<u>Observation</u>: In the case of study, the pushing force that causes the movement of the object is the vibration applied from the controller, as it has been seen along the experimental results.*

During this process, it causes some of the energy of motion to be converted into heat. This heat formed may cause the particles to dry, thus losing water, which leads to the previously demonstrated reduction of the moisture content of the material after runs.

## 2. ANNEXE 2: REPEATABILITY OF EXPERIMENTS

As for any experimental study carried out in a laboratory, in this study, the repeatability of the results was considered as one of the most important parameters to take care of. The evaluation of the repeatability of the results is a prerequisite for the latter to understand their intrinsic level of significance. If this last situation occurs, results are probably not taken into account because they do not allow to deduct any unequivocal conclusions. That is why it was decided to do under the same conditions numerous runs in order to evaluate from the set of values these following characteristic parameters:

- Mass flow averages for each run
- Mass flow average for all the runs
- Average ± 3*σ for each run
- Average ± 3*σ for all the runs

## 2.1 REPEATABILITY WITH 9% MOISTURE MATERIAL

Firstly, three runs were carried out with the same conditions (9% of moisture content, 10 mm of free height and 35% of intensity of vibration), obtaining Figure 2:

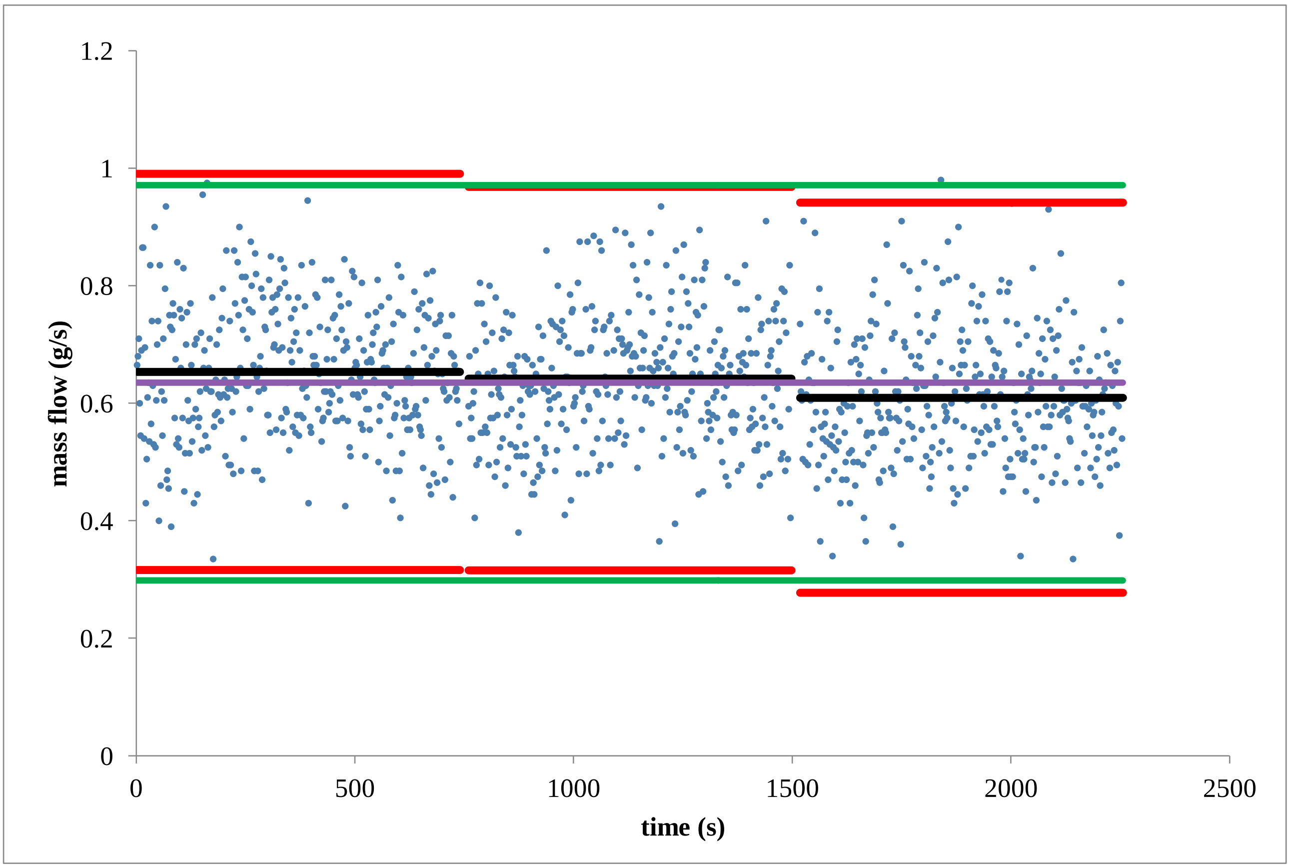


**Figure 2**. Repeatability experiment for 9% moisture, 10 mm of free height and 35% of intensity of vibration

In Figure 2, the different mass flows obtained along the three runs are represented by blue dots. These blue dots are inside the interval marked by the green lines, representing the average ± 3*σ of all the runs. This means the results are representative, because they don't present high variability between them. The same can be deduced from the proximity that individual parameters (averages by black lines and averages ± 3*σ by red lines) have with the general ones (average by purple line and average ± 3*σ by green lines).

## 2.2 REPEATABILITY WITH 12% MOISTURE MATERIAL

Other seven runs were carried out with other same conditions (12% of moisture content, 9 mm of free height and 42.5% of intensity of vibration), obtaining Figure 3:

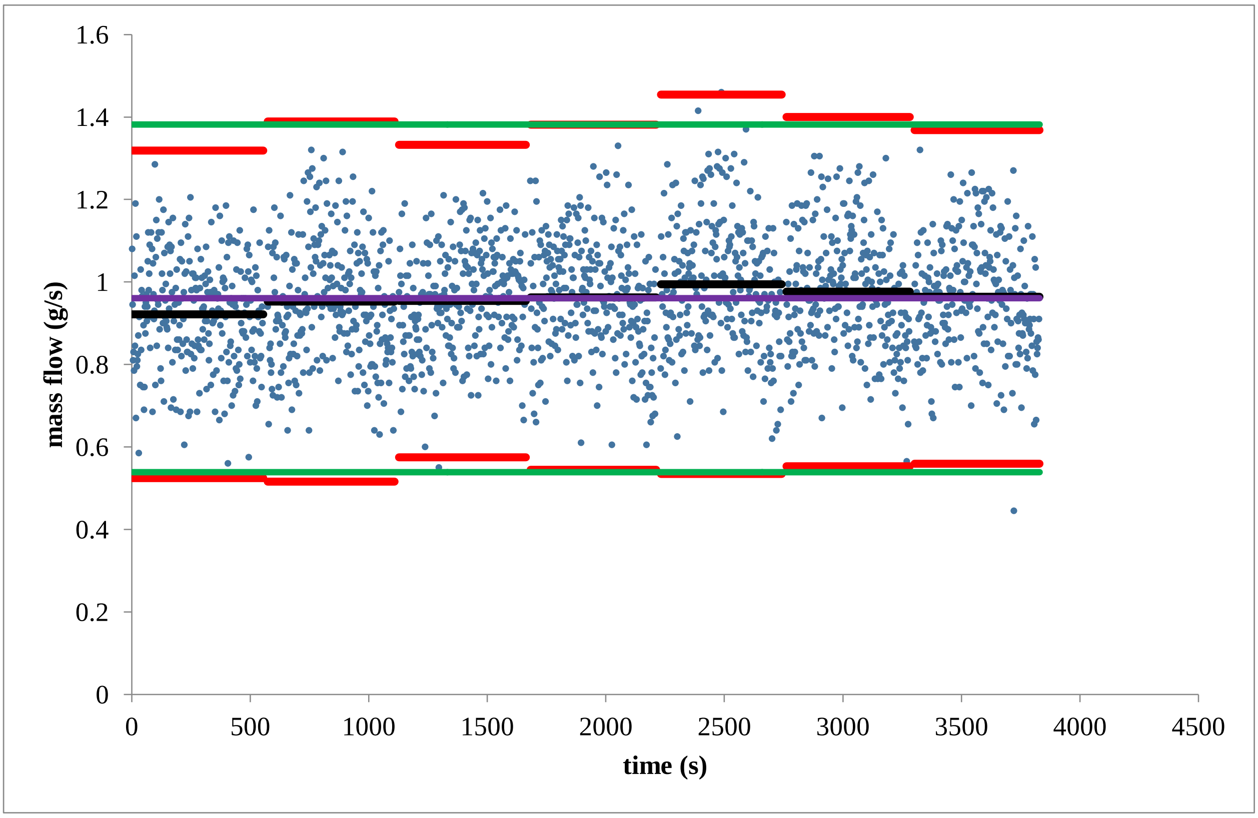


**Figure 3**. Repeatability experiment for 12% moisture, 9 mm of free height and 42.5% of intensity of vibration

However, in Figure 3 above, the situation is not so good. The individual averages ± 3*σ and averages are not so close to the general ones, which is translated to a higher variability of the results and then, to a lower precision of them. This repeatability experiment shows a higher variation of the results obtained under the news conditions established. From these conditions, and looking to Annexe 1, it is clear that the higher moisture content of this working material may be the responsible of this more variable behavior. This higher reduction of the moisture content in the 12% moisture material than in the 9% moisture material leads to more different conditions between different runs, leading to more variable results, and then less representative.

## 2.3 REPEATABILITY WITH 14% MOISTURE MATERIAL

This same behavior can be analyzed in another experiment realized this time with a 14% moisture material, 16 mm of free height and 40% of vibration intensity, represented in Figure 4 below.

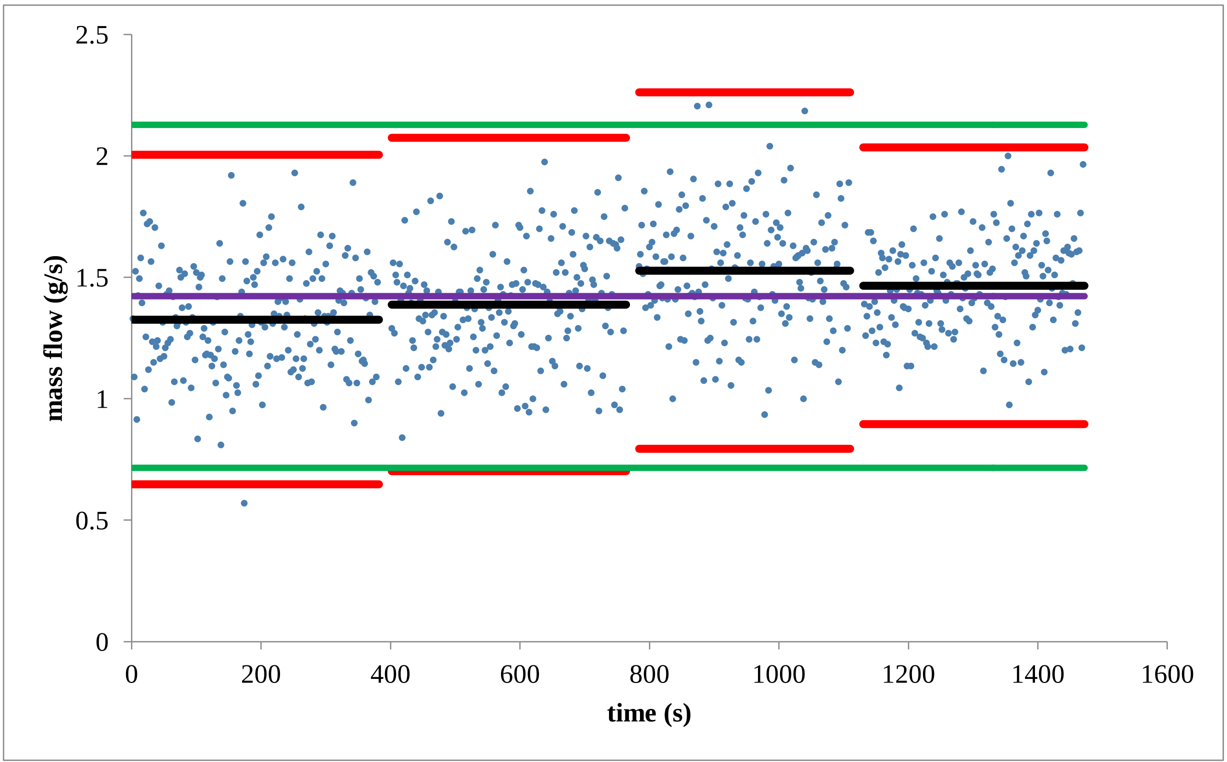


**Figure 4**. Repeatability experiment for 14% moisture, 16 mm of free height and 40% of intensity of vibration

In effect, even more variable results are obtained in this case with a 14% moisture material. This confirms the above mentioned; with a higher moisture content, higher is the reduction of the moisture and then more different are the conditions between each run, causing a higher variability in the results.

It was then realized that it would be more interesting to work with samples with lower moisture for the rest of experiments that require in most cases constant moisture content.

## 3. ANNEXE 3: LOOK FOR BEST EXPERIMENTAL CONDITIONS

Conducting the experiments was not so easy and fast. In effect, the preparation of all the set-up takes time, but it is not the only thing that had to be taken into account. Working with a material for the first time requires the study and knowledge of its behavior depending on multiple parameters that influence the experiment. After the multiple experiments realized, it is evident that a higher moisture material will require a higher free height between the tip of the hopper and the surface of the chute, or even a higher intensity of vibration than a lower moisture material, due to its lower flow capacity. Thus, choosing the conditions for the different experiments was not easy, because a little difference of the height or the vibration intensity could cause a blocking in the nozzle or even a mass flow value outside the desired range (between 30 g/min and 50 g/min normally). For this reason, it was important to know the material that would be used in in conjunction with the envisioned experiment, as well as the range of conditions that would lead to the expected mass flow, without any failure during the process.

This led to several runs of different conditions and different materials always looking for the best conditions that could later be used in the experiments from which a conclusion can be drawn.

## 4. ANNEXE 4: CALCULATION NEEDED FOR % OF INCLINATION

In *3.5* DETERMINATION OF HOPPER MASS FLOW IN FUNCTION OF THE INCLINATION OF THE CHUTE PLANE, it was talked about the angle of inclination of all the set-up to the table as the variable parameter whose influence in the mass flow was evaluated. For this, any kind of uniform laboratory tool could be used to put below the set-up and achieve the angle desired. Thus, from the set-up, a rectangular triangle can be formed as schemed in Figure 5 below.

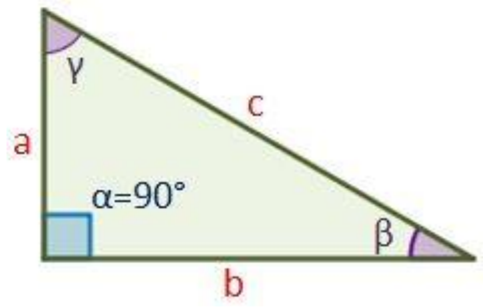


**Figure 5**. Example of a rectangular triangle

In this case, "a" would be the height achieved by the experimental tool and whose width is known, "b" the surface of the table and "c" the surface where all the set-up (hopper + chute + vibration device) is resting. Therefore, for the angle of inclination in % ($\beta$), apart doing some measurements in the laboratory with a ruler, it was necessary to apply the following [Eq. 5].

$$\text{Angle } \beta \text{ inclination (in \%)} = \frac{a}{b} \qquad \text{[Eq. 5]}$$