# Development of a new mechanism for uniform distribution of fines in a small-scale silo

Dariush Zare[1*], Arash Nourmohamadi-Moghadami[1], Richard. L. Stroshine[2]

1. Biosystems Engineering Department, School of Agriculture, Shiraz University, Shiraz, Iran.

2. Agricultural and Biological Engineering Department, 225 South University Street: Purdue University, West Lafayette, IN, 47907-2093, USA.

## Abstract

During top filling of a storage silo, granular material containing a range of particle sizes, the smaller particles (fine material) accumulate under the filling point. This interferes with air distribution preventing effective aeration of regions with higher percentages of fine material. In this work an innovative variable filling point (VFP) method was developed and tested as a means of reducing the non-uniform distribution of fine material during filling. The VFP mechanism produces rotational and diametric motion of the fill pipe using a rotating rim placed at the top of the experimental silo. Factors that were varied included initial BCFM ($BC_I$), volume flow rate of material ($Q$), fill pipe diameter ($D_F$) and ratio of rotational velocity of the rim to the linear velocity of the fill pipe ($V_R/V_L$). The findings of the VFP experiments demonstrated that the distribution of fine material became more uniform with increasing $V_R/V_L$, $BC_I$, $Q$, and with decreasing $D_F$. The comparison between CFP and VFP experiments showed that the proposed VFP filling method gave a more uniform distribution of fine material eliminating zones with high concentrations of fines.

**Key words**: Fine distribution, Material flow, Grain silo, Variable filling point

*Corresponding author

E-mail: dzare@shirazu.ac.ir

### Nomenclature

| | | | |
|---|---|---|---|
| $BC_I$ | initial percent BCFM | $V_R$ | corresponding linear velocity of the rotating rim (m $s^{-1}$) |
| $BC_L$ | local percent BCFM | $Z$ | scaled distance from the bottom of the silo (dimensionless) |
| DC | direct current | | |
| $D_F$ | fill pipe diameter (mm) | *Abbreviations* | |
| $NUF_R$ | non-uniformity factor for a ring (at a certain height in silo) | BCFM | broken corn and foreign material |
| $NUF_S$ | non-uniformity factor for a silo | CCW | counter clockwise |
| $Q$ | volume flow rate | CFP | central filling point |
| $R$ | scaled distance from the center of the silo (dimensionless) | CW | clockwise |
| $V_L$ | linear velocity of fill pipe outlet (m $s^{-1}$) | VFP | variable filling point |

## 1. Introduction

Granular materials containing a range of particle sizes, are particularly prone to segregate whenever these are processed, e.g., forming a heap (cone) in silos during top filling. When a centrally top filled silo is being filled with the granular material, larger particles tend to flow towards the silo wall while the smaller particles accumulate under the filling point [27]. The presence of fine material increases the airflow resistance of agricultural granular products [2,6,10,12,14], making these products more difficult to aerate or dry. The characteristics of fines in corn were discussed in the review paper by Bern and Hurburgh (1992) [2].

The localized concentration of fine material causes non uniform airflow in the grain mass. This decreases the specific airflow through the grain in the center of the grain mass compared to the periphery [1,9,17,22,26]. Inefficient drying and aeration due to lower airflow rate leads to higher temperatures and higher inter-seed relative humidity in zones with low air flow allowing the development of hotspot, mold, and insect infestations. Higher total airflows are required to increase the chances that an aeration system can push air into the core of the grain mass. Since fine material distribution is an important parameter affecting the flow of air through grain during aeration and drying [3], several procedures have been proposed to prevent non-uniform particle size distributions. These include coring [22] and pre-cleaning of grains [16]. Two filling procedures that have been proposed are leveling [16,18] and spreading [4,5,27,28].

Coring the grain mass is achieved by partially unloading the grain silo after filling by removing the localized concentration of fine material from the bottom center which leads to the development of an active channel about the outlet that reaches all the way to the upper grain surface. This can cause an inverted cone to form in the center of the bin resulting in more uniform distribution of airflow [17]. However, coring is not going to be effective for silos that are not filled or unloaded from the center. Researchers have demonstrated that lower airflow rates are needed for aeration in clean stored grain compared to grain with high levels of foreign materials [21]. During the cleaning process the lightweight trash, dockage and other foreign materials are removed. Since cleaning is a separate and additional process in the grain industry, it may not be cost effective in terms of time and cost. Loewer et al. (1994) used an auger-type grain spreader for uniform distribution of the fine material in a storage system. Leveling large bins by hand or shovel is impractical [18]. Stephens and Foster (1976) and Stephens and Foster (1978) used spinner-type spreaders to improve uniformity of airflow in storage bins [27,28]. They found that spreaders decreased the uniformity of fine material in sorghum while there was little difference in wheat. Thus, it can be inferred that spreader performance depends partly on the type of grain. Based on these observations, it seems appropriate to investigate methods of avoiding non-uniform distribution of fines during filling. One of the potential solutions could be employment of a new mechanism in filling process.

The grain depth, feeding rate, fill pipe (inlet) diameter and initial content of fine material have been reported as important parameters in the study of fine distribution during filling of silos or other storage systems [7,8,11,13,15,23,24,25]. The distribution of broken corn and foreign material (BCFM) in a small-scale silo filled from a central filling point (CFP) was investigated in previous work [20] where above mentioned parameters considered as independent variables. The main objective of the present study was to develop a new filling method that gives a more uniform distribution of fine material in silos. The results were also compared with those obtained from CFP method.

## 2. Material and methods

### *2.1. Description of the experimental facilities*

The experimental facilities were described in the first work [20]. In this study an innovative filling mechanism was developed and mounted on top of the experimental silo. It is called the “variable filling point” (VFP) mechanism, and it consists of moving the fill pipe continuously at the top of a silo during filling to achieve a more uniform distribution of fine material. The VFP mechanism produces a combination of linear and rotational motion of the fill pipe (Fig. 1). This mechanism is described in detail later in this section. The fill pipe consisted of two tubes, one flexible and one rigid, placed under the fluted roller mechanism. The bottom end of the fill pipe was attached to the VFP mechanism. The VFP mechanism (Fig. 1) consisted of a rotating rim with a diametric slit guide in the middle. The fill pipe reciprocated in the slit that ran along a diameter of the rotating rim. In addition, there was a mechanism to produce the reciprocating motion and a control unit system (Fig. 2 and Fig. 3).

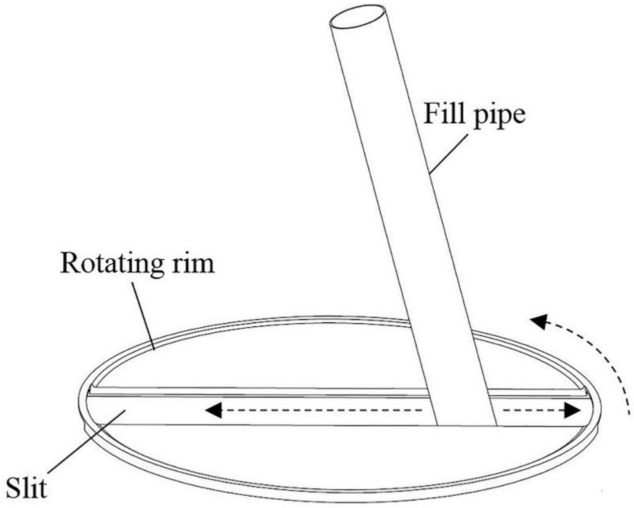

*Fig. 1.* ***A Schematic of VFP mechanism***

*Fig. 2.* ***Experimental set up (a) main container, (b) elevator, (c) trapezoidal container, (d) agitator, (e) fluted roller mechanism, (f) fill pipe, (g) reciprocating mechanism, (h) unit control system, (i) rotating rim (j) pilot scale silo consist of seven rings***

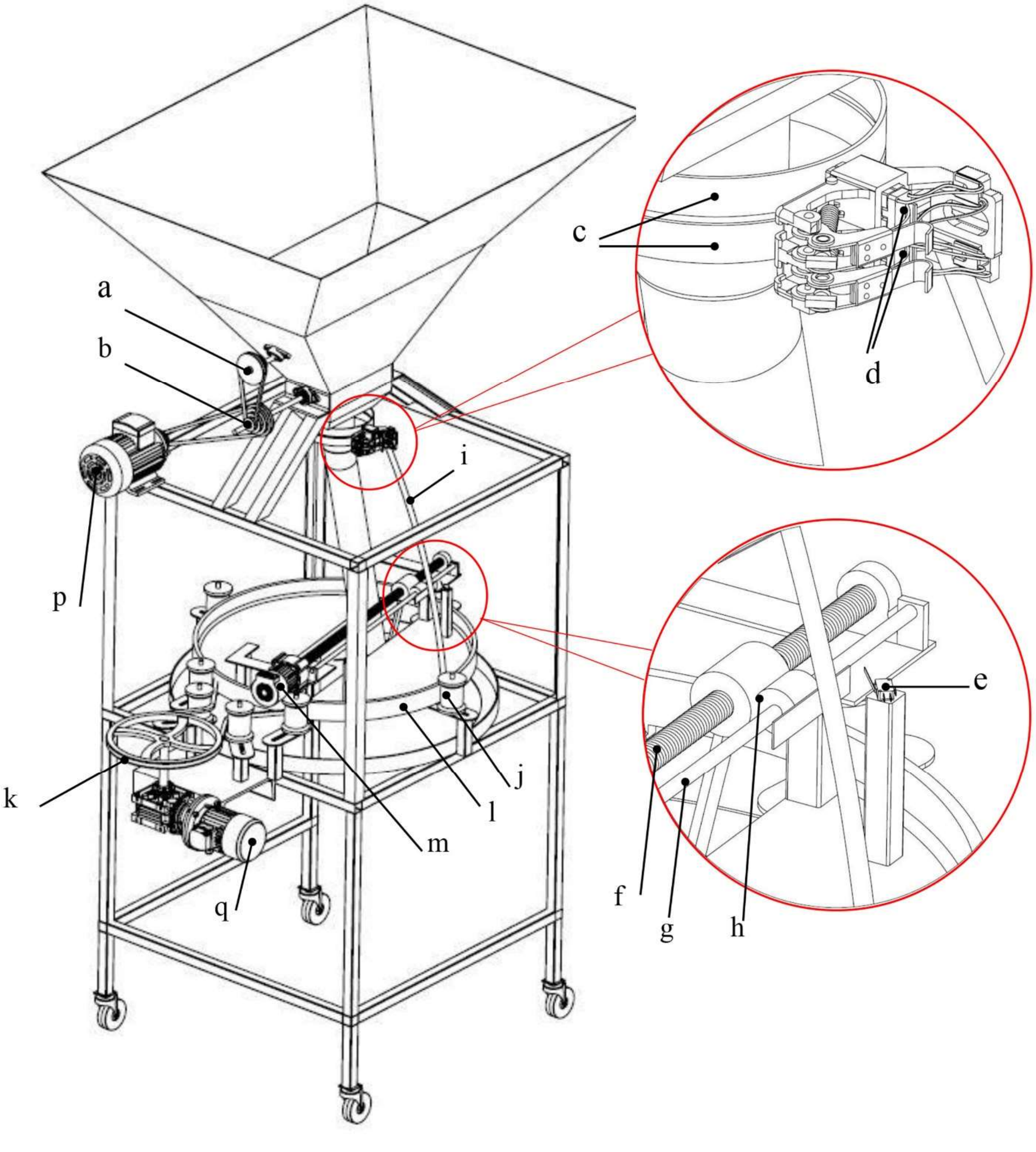

*Fig. 3.* ***A Schematic of the main part of the experimental set up (a) the agitator shaft, (b) a fluted roller feeding shaft, (c) copper rings, (d) brushes, (e) a switch control, (f) the ball screw shaft, (g) a linear guide rail, (h) a slider, (i) a supporting rod, (j) a roller, (k) a pulley system, (l) a rotating rim, (m) a DC motor, (p) a three phase motor for driving the fluted roller mechanism, (q) a three phase motor for driving the pulley system.***

The reciprocating mechanism consisted of a set of linear guide rails, a slider, a ball screw shaft and a DC motor (Fig. 3). A pulley system was used to transmit rotational motion from a three phase motor to the rotating rim. The rotating rim was constrained by using some rollers to prevent vertical and lateral movement. A DC motor was used to drive the reciprocating mechanism and a transformer supplied the electricity needed to drive the DC motor. The electric power was transmitted from transformer to DC motor via two brushes and a pair of copper rings. Brushes made contact with the ring and were rotated around the rings because they were connected to the ring by a supporting rod.

A control unit system (Fig. 2(h)) as well as two micro switches (Fig. 3(e)) were used to automate CW and CCW rotation of the DC motor which led to reciprocating movement of the slider. When the slider made contact with each micro switch, the rotation direction of the ball screw was reversed. The bottom end of the fill pipe was held by the slider and as the slider moved, it produced both diametric (linear) and rotational motion of the outlet. When the VFP mechanism was operating, the fill pipe traced out a *petal-shaped path* (rose curve) over the top of the silo (see Fig. 4). This led to a more uniform distribution of the fine material.

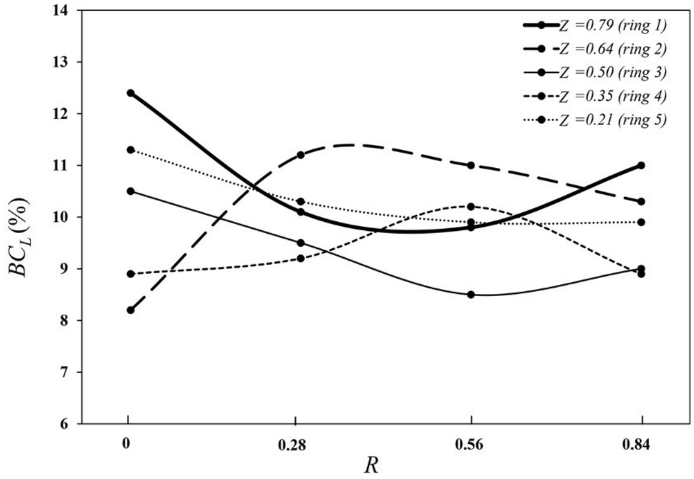

*Fig. 4.* ***Distribution profile of fine (*****$BC_L$*****) along radial direction at different heights (Z) in VFP method (for*** **$BC_I$** ***= 10%,*** **$V_R/V_L$*****=1,*** **Q** ***= 0.5 L*** **$s^{-1}$** ***and*** **$D_F$** ***= 120 mm).***

*2.2. Experimental procedure*

Details of the experimental procedure as well as the material properties are given in the first part of this work [20]. The effects of initial percent BCFM ($BC_I$), volume flow rate ($Q$), fill pipe diameter ($D_F$), and ratio of rotational velocity of the rim to the linear velocity of the fill pipe ($V_R/V_L$)[1] on local percent BCFM ($BC_L$) in both the radial and vertical directions were investigated. The linear velocity

---

[1] For determining different levels of this ratio, $V_R$ and $V_L$ corresponded to, respectively, the linear velocity of the rotating rim and the average linear velocity of the fill pipe.

of the fill pipe on the diameter of the rim changes from 0 when it first begins to move to a maximum of 0.84 m.s$^{-1}$ when the slider is about to touch the micro switch. It became 0 each time it touched a micro switch and reversed its motion. The linear velocity of the slider can be calculated from the pitch and the rotational velocity of the ball screw. The RPM of the ball screw was measured using a Testo 470 tachometer (Fotonic Corporation, Melrose, Massachusetts). To investigate different levels of $V_R/V_L$, the path of motion of the fill pipe was plotted using MATLAB (Mathworks, Inc., Natick, MA, USA) software (Fig. 5). The amplitude of the reciprocating motion of the fill pipe, the flow rate $Q$ and the levels of $V_R/V_L$ must be suitably chosen to prevent contact between the falling material and the silo wall. Considering all above-mentioned conditions, the amplitude of the motion of the fill pipe was 0.3 m. In addition, the three levels of $V_R/V_L$ were chosen as 0.5, 0.75, and 1, and the three levels of $Q$ were 0.5, 1, 1.5 L.s$^{-1}$. The tests were conducted with three levels of $BC_I$ which were 5, 7.5 and 10% and three levels of $D_F$ which were 84, 105 and 120 mm. The experiments were replicated three times. There were 126 runs in VFP experiments (Table 1).

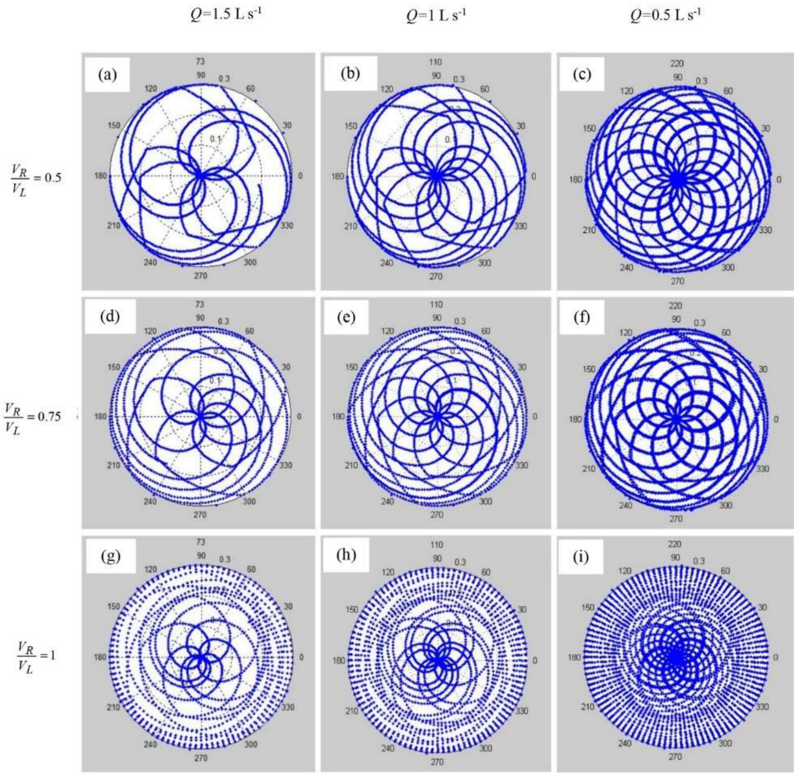

*Fig. 5*. ***Path followed by the end of the fill pipe for different ratios of the rotational velocity of the rim,*** $V_R$ ***to the linear velocity of the pipe,*** $V_L$.

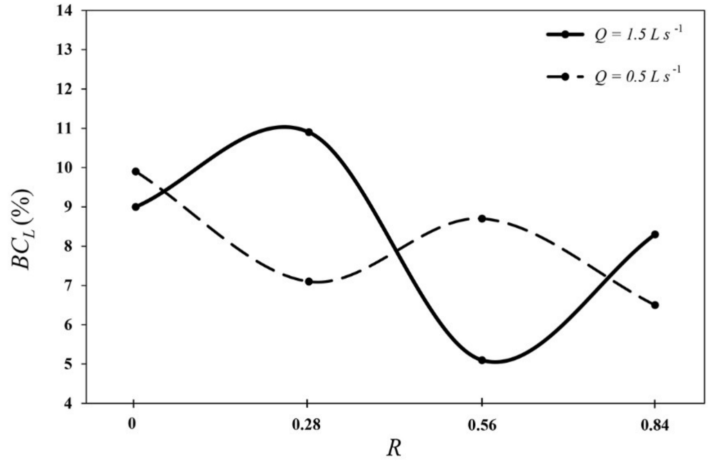

*Fig. 6.* ***Distribution profile of fine (*****$BC_L$*****) along radial direction for volume flow rates (*****Q*****), 0.5 and 1.5 L $s^{-1}$ in VFP method (for Z=0.64,*** **$BC_I$** ***= 7.5%,*** **$V_R/V_L$*****= 0.5 and*** **$D_F$** ***= 105 mm).***

## 3. Results and discussion

This section describes results of the VFP experiments including the distribution of fine material and the effects of the same three factors namely initial BCFM, volume flow rate of material and fill pipe diameter were evaluated in the CFP experiments. Also, the calculated non-uniformity factor (*NUF*) values for CFP experiments (reported in previous work [20] are given again in Table 1 for better comparison between VFP and CFP methods. Note that for the CFP experiments, only those values of *NUF* that correspond to the values of NUF for the VFP experiments are included in the table.

### *3.1. Distribution of fines along radial direction*

Fig. 5 gives the values of $BC_L$, local percent BCFM for the sampled locations (for a typical case, $BC_I$ = 10%, $V_R/V_L$=1, $Q$ = 0.5 L $s^{-1}$ and $D_F$ = 120 mm while the same trends were found for other rest cases), in the radial direction at different grain depths ($Z$ values). As the silo is being filled using the VFP method, the grain stream changes location making a petal-shaped pattern (Fig. 5) as it falls on the grain surface. The heap formed in CFP experiments is eliminated and only a small heap is formed briefly on the surface of the stationary bed and moves around on the top surface following the petal shaped pattern mentioned above. Therefore, the amount of sifting that occurs will be reduced. As can be seen in Fig. 4, the $BC_L$ values fluctuate irregularly along the radial direction. This is in contrast to the $BC_L$ trend in CFP experiments where it decreased near the silo wall. Therefore, when the silo is filled using the VFP method, the fines do not accumulate near the center of the silo and they are more uniformly distributed. As explained previously, a more uniform distribution of fines facilitates the aeration process. According to the values of non-uniformity factor given in Table 1, in all experiments, applying VFP method led to more uniform distribution of fine material (increase in *NUF*).

### *3.2. Effect of height*

Examination of the data in Table 1 reveals that, similar to what was observed in the CFP experiments, $NUF_R$ increased with increasing grain depth ($Z$) in all the VFP experiments. This is also depicted in Fig. 5. For instance, in row 1, when $Z$ increased from 0.21 to 0.79 $NUF_R$ increased from 16.2% to 38.1%. The velocity of the material falling onto the surface of the material in the silo decreases as the silo is being filled. The reason is the same as the one that was explained previously in CFP experiments [20]. For the bottom layers the falling material strikes the surface with more velocity resulting in a better distribution of the fine material. Another reason is that when the VFP mechanism is used, for the bottom layers (Z smaller), the material that falls onto the stationary surface is farther away from the center of the silo.

**Table 1.** Comparison of non-uniformity factor (*NUF*) when using VFP and CFP methods to fill the test silo. Other factors were varied as listed in order to achieve a wide range of experimental conditions.

| No. | $BC_I$ (%) | $Q$ (L s$^{-1}$) | $D_F$ (mm) | $Z$ | $NUF_R$ (%) | | | | $NUF_S$ (%) | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | VFP | | | CFP | VFP | | | CFP |
| | | | | | $V_R/V_L$ | | | | $V_R/V_L$ | | | |
| | | | | | 0.5 | 0.75 | 1 | | 0.5 | 0.75 | 1 | |
| 1 | 5 | 0.5 | 84 | 0.79 | 38.1 | 31.6 | 27.7 | 162.8 | 27.7 | 25.0 | 20.4 | **122.2**[a] |
| | | | | 0.64 | 35.4 | 33.6 | 25.1 | 144.0 | | | | |
| | | | | 0.50 | 28.4 | 27.1 | 18.8 | 124.1 | | | | |
| | | | | 0.35 | 20.6 | 19.9 | 18.7 | 101.8 | | | | |
| | | | | 0.21 | 16.2 | 12.7 | 11.5 | 78.0 | | | | |
| 2 | 5 | 0.5 | 105 | 0.79 | 30.4 | 29.9 | 23.4 | 159.6 | 21.4 | 19.6 | 18.7 | 119.6 |
| | | | | 0.64 | 24.1 | 24.6 | 26.4 | 142.1 | | | | |

| | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | 0.50 | 25.1 | 18.2 | 20.9 | 123.6 | | | | |
| | | | | 0.35 | 17.3 | 17.5 | 11.9 | 98.2 | | | | |
| | | | | 0.21 | 10.2 | 7.8 | 11.0 | 74.3 | | | | |
| 3 | 5 | 0.5 | 120 | 0.79 | 20.8 | 21.7 | 18.0 | 145.4 | 17.6 | 14.0 | 12.7 | 110.4 |
| | | | | 0.64 | 20.9 | 14.8 | 17.4 | 135.5 | | | | |
| | | | | 0.50 | 21.4 | 16.2 | 11.5 | 116.9 | | | | |
| | | | | 0.35 | 14.5 | 11.3 | 11.0 | 92.2 | | | | |
| | | | | 0.21 | 10.4 | 5.8 | 5.3 | 61.8 | | | | |
| 4 | 7.5 | 0.5 | 105 | 0.79 | 30.9 | 28.4 | 23.3 | 100.5 | 23.0 | 20.6 | 17.6 | 78.8 |
| | | | | 0.64 | 27.1 | 24.6 | 21.4 | 91.6 | | | | |
| | | | | 0.50 | 24.8 | 20.3 | 17.9 | 80.9 | | | | |
| | | | | 0.35 | 17.4 | 16.4 | 15.0 | 67.3 | | | | |
| | | | | 0.21 | 14.7 | 13.5 | 10.3 | 53.8 | | | | |
| 5 | 7.5 | 1 | 105 | 0.79 | 32.6 | 29.4 | 27.0 | 94.2 | 23.9 | 21.8 | 19.5 | 72.6 |
| | | | | 0.64 | 27.1 | 26.8 | 23.6 | 86.0 | | | | |
| | | | | 0.50 | 23.6 | 20.4 | 19.7 | 74.9 | | | | |
| | | | | 0.35 | 20.1 | 19.8 | 15.5 | 61.3 | | | | |
| | | | | 0.21 | 16.1 | 14.9 | 11.6 | 46.7 | | | | |
| 6 | 7.5 | 1.5 | 105 | 0.79 | 32.7 | 32.8 | 30.0 | 78.2 | 24.4 | 22.5 | 21.3 | 53.6 |
| | | | | 0.64 | 29.9 | 27.6 | 26.6 | 68.0 | | | | |
| | | | | 0.50 | 25.3 | 21.9 | 22.0 | 55.2 | | | | |
| | | | | 0.35 | 20.6 | 17.1 | 17.2 | 40.5 | | | | |
| | | | | 0.21 | 13.3 | 13.0 | 10.9 | 26.0 | | | | |
| 7 | 5 | 1.5 | 84 | 0.79 | 41.7 | 38.4 | 32.2 | 111.9 | **30.5**$^{c}$ | 26.3 | 24.5 | 80.8 |
| | | | | 0.64 | 34.9 | 29.0 | 29.3 | 98.9 | | | | |

| | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | 0.50 | 31.3 | 26.5 | 26.0 | 83.0 | | | | |
| | | | | 0.35 | 27.0 | 23.3 | 20.2 | 65.9 | | | | |
| | | | | 0.21 | 17.6 | 14.0 | 14.8 | 44.1 | | | | |
| 8 | 7.5 | 1.5 | 84 | 0.79 | 34.7 | 34.3 | 30.4 | 82.3 | 28.2 | 26.0 | 23.7 | 56.6 |
| | | | | 0.64 | 33.3 | 34.1 | 25.9 | 72.0 | | | | |
| | | | | 0.50 | 26.9 | 24.4 | 22.4 | 57.6 | | | | |
| | | | | 0.35 | 27.6 | 20.2 | 21.9 | 42.7 | | | | |
| | | | | 0.21 | 18.6 | 16.9 | 18.0 | 28.2 | | | | |
| 9 | 10 | 1.5 | 84 | 0.79 | 29.3 | 26.5 | 24.1 | 63.2 | 22.7 | 21.8 | 19.5 | 47.2 |
| | | | | 0.64 | 29.0 | 23.7 | 26.6 | 56.0 | | | | |
| | | | | 0.50 | 22.9 | 19.3 | 17.6 | 47.7 | | | | |
| | | | | 0.35 | 16.4 | 21.6 | 16.8 | 38.5 | | | | |
| | | | | 0.21 | 16.0 | 18.1 | 12.2 | 30.3 | | | | |
| 10 | 7.5 | 1 | 84 | 0.79 | 35.4 | 34.0 | 30.0 | 100.5 | 29.1 | 27.1 | 23.9 | 78.8 |
| | | | | 0.64 | 33.2 | 31.6 | 26.7 | 91.6 | | | | |
| | | | | 0.50 | 28.7 | 28.6 | 25.2 | 80.9 | | | | |
| | | | | 0.35 | 27.6 | 21.5 | 21.4 | 67.3 | | | | |
| | | | | 0.21 | 20.3 | 19.7 | 16.4 | 53.8 | | | | |
| 11 | 7.5 | 1 | 120 | 0.79 | 25.7 | 24.3 | 20.0 | 86.6 | 18.0 | 16.0 | 14.0 | 59.5 |
| | | | | 0.64 | 23.8 | 19.8 | 16.3 | 74.2 | | | | |
| | | | | 0.50 | 19.3 | 15.5 | 14.7 | 59.8 | | | | |
| | | | | 0.35 | 12.4 | 10.9 | 10.1 | 46.0 | | | | |
| | | | | 0.21 | 8.8 | 9.5 | 8.7 | 31.1 | | | | |
| 12 | 10 | 0.5 | 120 | 0.79 | 20.2 | 16.8 | 14.8 | 84.6 | 15.1 | 13.9 | **11.2$^{d}$** | 63.7 |
| | | | | 0.64 | 18.4 | 15.7 | 12.2 | 79.7 | | | | |

| | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | 0.50 | 14.3 | 14.9 | 11.4 | 70.5 | | | | |
| | | | | 0.35 | 14.5 | 12.7 | 9.5 | 51.7 | | | | |
| | | | | 0.21 | 8.1 | 9.4 | 7.8 | 32.0 | | | | |
| 13 | 10 | 1 | 120 | 0.79 | 25.1 | 22.3 | 18.3 | 67.4 | 18.4 | 16.3 | 15.2 | 45.3 |
| | | | | 0.64 | 21.4 | 19.2 | 18.4 | 56.6 | | | | |
| | | | | 0.50 | 17.7 | 15.3 | 15.2 | 44.8 | | | | |
| | | | | 0.35 | 14.3 | 13.7 | 14.1 | 34.6 | | | | |
| | | | | 0.21 | 13.5 | 10.9 | 10.2 | 24.3 | | | | |
| 14 | 10 | 1.5 | 120 | 0.79 | 27.7 | 24.0 | 21.6 | 50.4 | 20.8 | 19.1 | 16.3 | **37.0**[b] |
| | | | | 0.64 | 21.9 | 23.2 | 20.2 | 45.1 | | | | |
| | | | | 0.50 | 21.3 | 19.8 | 16.6 | 38.7 | | | | |
| | | | | 0.35 | 17.5 | 16.0 | 12.8 | 29.4 | | | | |
| | | | | 0.21 | 15.7 | 12.4 | 10.5 | 21.2 | | | | |

[a]: Highest value of $NUF_S$ in CFP experiments

[b]: Lowest value of $NUF_S$ in CFP experiments

[c]: Highest value of $NUF_S$ in VFP experiments

[d]: Lowest value of $NUF_S$ in VFP experiments

### *3.3. Effect of initial BCFM*

According to the data given in Table 1, the values of $NUF_S$ decreased with an increase in the initial percentage of BCFM. For example, for $Q = 1.5$ L.s$^{-1}$, $DF = 84$ mm and $V_R/V_L = 0.5$, when $BC_I$ increases from 5% to 10% (rows 7 to 9), the value of $NUF_S$ decreased from 30.5% to 22.7%. The smaller the heap the shorter the length of the flowing layer, and similar to the discusion for CFP experiments in Nourmohamadi-Moghadami et al. 2019 [19] when $BC_I$ increases, the penetration of the fines into the lower layer along the surface of the momentary heap decreases. Because the heap formed is smaller when the silo is filled using the VFP method, the effect of $BC_I$ is less prononced compared to when the silo is filled using the CFP method.

### 3.4. Effect of $V_R/V_L$

As shown in Fig. 5 the ratio of the rotational velocity of the rim, $V_R$ to the linear velocity of the end of the filling pipe, $V_L$, affects the pattern that the filling pipe makes as it travels to different positions over the top suface of the silo. In all the VFP experiments, $NUF_S$ decreased as $V_R/V_L$ increased. As an example, in row 1 (Table 1) when $V_R/V_L$ increased from 0.5 to 1 $NUF_S$ decreased from 27.7% to 20.4%. Fig. 5 shows the petal-shaped path of the bottom of the fill pipe at different values of $V_R/V_L$ and $Q$ which was simulated in MATLAB software based on the capacity of a ring from the experimental silo and the volume flow rate of the material. The effect of volume flow rate will be discussed in the next section. As it is clear in the figure that when $V_R/V_L$ increases, the petals become wider (more scattered) as the fill pipe moves across the silo cross sectional area. In other words, at higher values of $V_R/V_L$, the fill pipe has a greater angular displacement (or in general, displacement) on the plane perpendicular to the silo central axis compared to the displacment for lower values of $V_R/V_L$. Therefore, the fine material is distributed more uniformly because it is distributed across a greater area on the surface of the stationary material.

### 3.5. Effect of volume flow rate

Fig. 6 gives the values of $BC_{L,}$ local percent BCFM for the sampled locations for two levels of volume flow rates, 0.5 and 1.5 $L.s^{-1}$ (for a typical case, $BC_I = 7.5\%$, $V_R/V_L= 0.5$, $Z = 0.64$ and $D_F =$ 105 mm while the same trends were found for other rest cases), in the radial direction at different grain depths ($Z$ values). As can be seen by examining Table 1, $NUF_S$ increases with increasing volume flow rate for VFP filling. For example, for $BC_I = 7.5\%$, $D_F = 105$ mm and $V_R/V_L = 1$ (row 4 to 6) when $Q$ varied from 0.5 to 1 $L.s^{-1}$, $NUF_S$ increased from 17.6% to 21.3%. This is the opposite trend compared to the results obtained from the CFP experiments [20] where, $NUF_S$ decreases with increasing volume flow rate. The corresponding values for the CFP experiments decreased from 78.8% to 53.6%. This can be justified as follows. When a silo is filled with a flow rate of 0.5 $L.s^{-1}$, it takes 220 s to fill a ring, whereas, this time decreased to about 73 s for a volume flow rate of 1.5 $L.s^{-1}$. This indirectly affects the fine material distribution because, as shown in Fig. 5, at lower volume flow rates, the VFP mechanism can run for a longer time than it does at higher volume flow rates. This additional time allows the fines to be distributed more uniformly.

### *3.6. Effect of fill pipe diameter*

$NUF_S$ decreases as the fill pipe diameter increases. Comparing the data in rows 1 to 3 of Table 1, $NUF_S$ decreased from 25% to 14% for $V_R/V_L$ of 0.75 when the fill pipe diameter increased from 84 to 120 mm. The larger the diameter of the fill pipe, the larger the cross sectional area of the stream of falling material. Therefore fines can land on a larger area on the surface of the stationary bed and this leads to more uniformity in fine distribution.

Since lower values of $NUF_S$ are desirable, it can be stated that the combination of higher values of $BC_I$, $V_R/V_L$, $D_F$ and lower values of $Q$ increase the uniformity of the distribution of fine material for the VFP filling. However, it is important to note that lower percentages of fine material ($BC_I$) are actually desirable for stored grains. The lowest value of $NUF_S$ (11.2%) was for $BC_I = 10\%$, $Q = 0.5$ L.s$^{-1}$, $D_F = 120$ mm and $V_R/V_L = 1$ (row 12 in Table 1). Conversely, the highest value of $NUF_S$ (30.5%) was for $BC_I = 5\%$, $Q = 1.5$ L.s$^{-1}$, $D_F = 84$ mm and $V_R/V_L = 0.5$ (row 7 in Table 1).

## 4. Conclusions

In this study an innovative filling method, the variable filling point (VFP) method was proposed and tested as a means of attaining a more uniform distribution of fine material in a small scale silo. The VFP mechanism produces rotational and diametric motion of the fill pipe using a rotating rim placed at the top of the silo. The effects of the parameters namely initial percent BCFM, volume flow rate, fill pipe diameter and ratio of rotational velocity of the rim to the linear velocity of the fill pipe were investigated. The results indicated that the distribution of fine material becomes more uniform with increasing ratio of rotational velocity of the rim to the linear velocity of the fill pipe, initial percent BCFM, and volume flow rate, and with decreasing fill pipe diameter. The comparison between CFP (conducted in previous work) [20] and VFP experiments showed that the proposed filling method increases the uniformity of fine material distribution during filling of silos. Therefore, by applying the proposed filing method, the zones with high concentration of fines can be eliminated which means there will be a more uniform distribution of airflow in stored grain during aeration.

## 5. Recommendations for future studies

In the variable filling point method, it was observed that non-uniformity decreased with decreasing volume flow rate of material into the silo. However, an economic analysis was not conducted nor was the energy consumption determined. This is important because at lower flow rates the filling mechanism must be run for a longer time period in order to fill a silo. More study is needed to clarify this issue. Also, it is recommended to carry out some aeration experiments to investigate more accurately the effects of fine distribution on air distribution in a silo filled with variable filling point method.

## References

1. Bartosil, R. E., and Maier, D. E. 2006. Effect of airflow distribution on the performance of NA/LT in-bin drying of corn. *Transactions of the ASABE*, *49*(4), 1095-1104.
2. Bern, C. J., and Hurburgh Jr., C. R. 1992. Characteristics of fines in corn: review and analysis, *Transactions of ASAE*, *35*(6), 1859–1867.
3. Chang, C. S., Converse, H. H., and Lai, F. S. 1986. Distribution of fines and bulk density of corn as Affected by choke-flow, spout-flow, and drop-height, *Transactions of ASAE*, *29*, 618–620.
4. Chang, C. S., Converse, H. H., and Martin, C. R. 1983. Bulk properties of grain as affected by self-propelled rotational type grain spreaders, *Transactions of ASAE, 26*(5), 1543–1550.
5. Chang, C. S., Shackelford, L. E., Lai, F. S., Martin, C. R., and Miller, B. S. 1981. Bulk properties of corn as affected by multiple-point grain spreaders, *Transactions of ASAE, 24*(6), 1632–1636.
6. Chung, D. S., Maghirang, R. G., Kim, Y. S., and Kim, M. S. 2001. Effects of moisture and fine material on static pressure drops in a bed of grain sorghum and rough rice, *Transactions of ASAE*, *44*(2), 331–336.
7. Combarros, M. G., Feise H. J., Strege, S., and Kwade, A. 2016. Segregation in heaps and silos: Comparison between experiment, simulation and continuum model. *Powder Technology, 293*, 26-36.

8. Engblom, N., Saxen, H., Zevenhoven, R., Nylander, H., and Enstad, G. G. 2012. Segregation of powder mixtures at filling and complete discharge of silos. *Powder Technology, 215-216*, 104-116.

9. Garg, D. 2005. *Modeling non-uniform airflow and its application for partial chilled aeration using PHAST-FEM*. MS thesis. West Lafayette, Indiana: Purdue University.

10. Giner, S. A., and Denisienia, E. 1996. Pressure drop through wheat as affected by Air velocity, moisture content and fines, *Journal of Agricultural Engineering Research*, *63*, 73–86.

11. Gray, J. M. N. T., and Hutter, K. 1997. Pattern formation in granular avalanches, Continuum Mechanics and Thermodynamics, *9*(6), 341–345.

12. Haque, E., Foster, G. H., Chung, D. S., and Lai, F. S. 1978. Static pressure drop across a bed of corn mixed with fines, *Transactions of ASAE, 21*, 997–1000.

13. Jain, A., Metzger, M. J., and Glasser, B. J. 2013. Effect of particle size distribution on segregation in vibrated systems. *Powder technology, 237*, 543-553.6

14. Jayas, D. S., Sokhansanj, S., Moysey, E. B., and Barber, E. M. 1987. Distribution of foreign material in canola bins using a spreader or spout. *Canadian Agricultural Engineering*, *29*, 183-188.

15. Koeppe, J. P., Enz, M. and Kakalios, J. 1998. Phase diagram for avalanche stratification of granular media. *Physical Review E 58*, R4104–R4107.

16. Kumar, A., and Muir, W. E. 1986. Airflow resistance of wheat and barley affected by airflow direction, filling method and dockage, *Transactions of ASAE*, *29*, 1423–1426.

17. Lawrence, J., and Maier, D. E.. 2011. Three-dimensional airflow distributions in peaked, leveled and cored grain mass configurations. *Biosystems Engineering, 110*(3), 321-329.

18. Loewer, O. J., Bridges, T. C., and Bucklin, R. A. 1994. *On-Farm Drying and Storage Systems*, ASAE, Pam DeVore-Hansen, Acquisitions Books and Journals.

19. Nourmohamadi-Moghadami, A., Zare, D., Singh, C. B. Stroshine, R. L. 2020. Filling of a grain silo. Part I: Investigation of fine material distribution in a small-scale center filled silo, *Biosystems Engineering*. 191: 145-156.

20. Noyes, R., Navarro, S., and Armitage, D. 2002. Supplemental aeration systems. In S. Navarro, and R. Noyes (Eds.), *The mechanics and physics of modern grain aeration management* (pp. 413-488). Boca Raton: CRC Press.

21. Noyes, R. T., and Kenkel, P. 1999. *Storing moist wheat at commercial elevators in Oklahoma*, OSU Current Report, CR-1741, Cooperative Extension Service, Oklahoma State University.

22. Olatunde, G. Atungulu, G. G., and Sadaka, S. 2016. CFD modeling of air flow distribution in rice bin storage system with different grain mass configurations, *Biosystems Engineering*, *151*, 286–297.

23. Schulze, D. 2008. *Powders and Bulk Solids - Behaviour, Characterization, Storage and Flow*, Verlag Berlin Heidelberg: Springer, (chapter 13).

24. Shinohara, K., Golman, B., and Nakata, T. 2001. Size segregation of multicomponent particles during the filling of a hopper, *Advanced Powder Technology*, *10*(1), 333-343.

25. Shinohara, K., and Golman, B. 2002. Segregation indices of multi-sized particle mixtures during the filling of a two-dimensional hopper, *Advanced Powder Technology, 13*(1), 93-107.

26. Siebenmorgen, T. J., and Jindal, V. K. 1987. Airflow resistance of rough rice as affected by moisture content, fines concentration and bulk density, *Transactions of ASAE*, *30*(4), 1138–1143.

27. Stephens, L. E., and Foster, G. H. 1976. Grain bulk properties as affected by mechanical grain spreaders, *Transactions of ASAE, 19*(2), 354–358.

28. Stephens, L. E., and Foster, G. H. 1978. Bulk properties of wheat and grain sorghum as affected by a mechanical grain spreader, *Transactions of ASAE, 21*(6), 1217–1221.