Flow patterns of cohesive feed in a model bin with flow-corrective inserts

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Zhang, Q., Hao, B. and Britton, M.G. 2002. **Flow patterns of cohesive feed in a model bin with flow-corrective inserts**. Canadian Biosystems Engineering/Le génie des biosystèmes au Canada **44**:5.1-5.6. Tests were performed to study the flow behaviour of cohesive feed in a model bin with bin inserts. The 2.4-m high rectangular bin, with cross section of 0.4 m x 1.0 m and a shallow hopper of 60°, was constructed from plywood and plexiglass so that the transparent front wall allowed the material movement to be observed and recorded by a video camera. Captured video images were then digitized to determine the flow patterns and velocity profiles. Compared with flow from the bin with no inserts, discharge of cohesive feed was more consistent when an insert was installed. Specifically, no permanent arching occurred; little variation was observed between test replicates; and the discharge rate increased 53% when an insert was installed at the bin-hopper transition (BHT). The insert was more effective in reducing arching when installed near BHT than other locations. When the insert was allowed to swing in the bin (rotating insert), it oscillated (±2°) during discharge. This oscillating motion prevented stable arches from forming. The bin insert changed the material flow from the funnel to mass flow mode. However, feed did flow uniformly inside the bin. The insert divided feed into two flow channels, with a fast channel on the left side of the bin and a slow one on the right. **Keywords:** flow, cohesive powder, feed, bin insert, video image.

Des tests ont été menés pour étudier le comportement en écoulement de moulée cohésive dans un silo modèle auquel on a ajouté un empiècement. Le silo rectangulaire de 2.4 m de haut, avec une section de 0.4 m x 1.0 m, et une trémie peu profonde de 60°, a été construit en contreplaqué et plexiglass. Un mur frontal transparent permettait d'observer et de filmer sur vidéo les mouvements de la moulée. Les images vidéo ont été numérisées afin de déterminer les schémas d'écoulement et les profils de vitesse. En comparant avec l'écoulement dans un silo conventionnel, on a observé que le déversement de la moulée cohésive se faisait plus régulièrement lorsqu'un empiècement était installé. Plus spécifiquement, aucune arche permanente ne s'est formée, on a observé peu de variations entre les répétitions, et l'installation d'un empiècement à la jonction du silo et de la trémie a permis d'augmenter la vitesse d'évacuation de 53%. C'est à cet endroit que l'installation de l'empiècement est la plus efficace pour réduire la formation d'arches. Lorsqu'on permettait à l'empiècement de se balancer dans le silo, (empiècement rotatif), il oscillait (±2°) durant le déchargement. Ces oscillations empêchaient la formation d'arches stables. Avec l'introduction de l'empiècement dans le silo, on est passé d'un patron d'écoulement en entonnoir à un patron d'écoulement de masse. Cependant, l'écoulement de la moulée dans le silo se faisait de manière uniforme. L'empiècement divisait la moulée selon deux canaux d'écoulement: un canal rapide du côté gauche et un canal lent du côté droit.

INTRODUCTION

Gravity discharge is commonly used in the agriculture and food industry to unload bulk materials from storage bins. Flow problems often occur because of improper bin design. The most common problems associated with gravity discharge of cohesive materials are arching and ratholing, which may result in inconsistent material delivery or interruption of production operations. These problems are generally caused by undesired material flow patterns in bins. Depending on the bin shape, roughness of its interior surfaces, and properties of the stored material, several patterns of material flow are possible. The two principal ones are funnel flow and mass flow. Funnel flow is defined as flow from a bin in which all material movement occurs through a central core with no movement occurring along the bin wall, while mass flow is described as flow from a bin in a manner such that material movement occurs along all or part of the bin wall (ASAE 1998a). Various methods have been used to correct flow problems by changing the flow pattern in the bin. Bin inserts are an economic flow correcting device (Johanson 1966, 1982). Bin inserts are objects, such as inverted cones and pyramids, placed inside bins to alter material flow, thus achieving desirable flow patterns. Proper selection and installation of bin inserts may provide a quick, practical solution to the problem of a poorly flowing bin. However, the success of using bin inserts requires the understanding of how an insert alters material flow in the bin.

In this study, computer image techniques were used to determine the flow patterns of cohesive feed in a model bin equipped with bin inserts. Compared with other techniques that have been used in studying bulk solids flow, such as visual and photographic observations, and x-ray techniques (O'Callaghan 1960; Giunta 1969; Brown and Richards 1970; Bransby and Blair-Fish 1974; Moriyama 1983; McLean et al. 1985; Schwab et al. 1989; Bucklin et al. 1991), the computer image techniques are better suited for quantitative measurement of flow velocity.

The specific objectives of this study were: (1) to investigate the influences of bin inserts on discharge and flow patterns of cohesive feed in a model bin, and (2) to determine the effects of the insert mounting location and method on the flow behaviour of cohesive feed.

EXPERIMENTAL METHODOLOGY

The experiment was conducted using a 2.4-m high model bin with a rectangular cross section of 0.4 m x 1.0 m (Fig. 1). A small cross-sectional depth of 0.4 m was used to simulate two-dimensional flow, i.e., flow was assumed to be uniform between the front and back walls of the bin. The front wall of the bin was made of transparent plexiglass for flow observations. To obtain the same friction on all the inside surfaces of the bin, the other

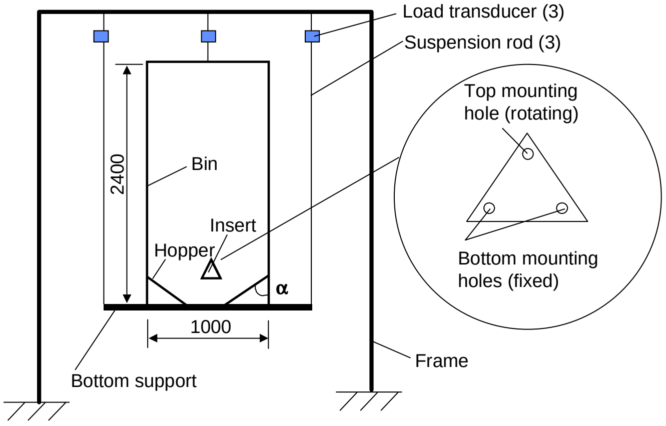

Fig. 1. Schematics of model bin test setup.

three walls, made of plywood, were lined with thin plexiglass panels. Three rows of angle iron bars were used to gird the front and rear walls to maintain the rigidity of the walls, thus minimizing the influence of the wall deformations on flow. The reinforcement kept the wall deflections within 1% of the bin width when the bin was fully filled.

Two plywood plates were placed inside the bin to form a two-dimensional wedge hopper (Fig. 1). The hopper plates were also lined with plexiglass to maintain uniform friction inside the bin. The hopper half-angle (α) could be adjusted by moving the two plates. In this study, a relatively shallow hopper with a hopper half-angle of 60° was used intentionally to create arching or ratholing in the bin so that the effectiveness of bin inserts could be observed. A slot discharge outlet 38 mm wide and 400 mm long (running from the front wall to the back wall) was used in all tests. To monitor the real time discharge rate, the model bin was suspended from a steel frame so that the entire weight of the bin structure and the stored material could be measured continuously by three load transducers (Fig. 1).

Inverted cones are one of the most common types of bin inserts used in industries. A triangular prism was used to simulate inverted cones in two-dimensional conditions. The plexiglass insert (prism) was 400 mm long (same as the cross-sectional depth of the bin) with a triangular cross-section of 100 mm on the three sides, which simulated an inverted cone 87 mm high, with an apex angle of 60°. Three holes were drilled at each end of the insert for mounting. The top hole was used to mount the insert so that it could swing sideways, whereas the insert was fixed in the bin if it was mounted by using the two bottom holes (Fig. 1). In both fixed and rotating (swinging) mounting configurations, the insert was mounted along the vertical axis of symmetry of the bin.

Table 1. Physical properties of ground feed used in experiment.

Property	Value[#]
Bulk density (kg/m^3)	639 (21)[*]
Angle of internal friction (degrees)	27 (0.5)
Angle of wall friction (degrees)	11 (0.2)
Cohesion (kPa)	1.6 (0.3)
Moisture content (% wb)	10.8 (0.1)

[#] Means of three measurements

[*] Values in parentheses are standard deviations

To determine the effect of mounting location on the effectiveness of the insert, the insert was tested at four mounting heights: L=126, 196, 280, and 476 mm (measured from the centre of the insert to the discharge outlet). The lowest level of 126 mm was the location where the insert could be placed as close to the discharge outlet as physically possible. When the insert was installed at this level, the gap between the hopper wall and the bottom of the insert was 5 mm greater than the width of the discharge opening. The insert was completely inside the hopper when it was installed 196 mm above the outlet. At 280 mm, the insert was at the level of the bin-hopper transition. At the highest level (476 mm), the insert was entirely outside the hopper. To show the insert location relative to the bin-hopper transition, the four mounting heights were expressed as fractions of the hopper height (H=280 mm) as follows: L/H = 0.45, 0.70, 1.00, and 1.70 for 126, 196, 280, and 476 mm mounting heights, respectively. After completing the first series of tests in which the insert was fixed in the bin, it was found that arching occurred for all mounting heights except L/H=1.00.

To examine whether flow could be improved by allowing the insert to swing (rotate), tests were performed with a rotating insert mounted at L/H = 0.70. In total, six insert mounting configurations were tested and three replicates were performed for each mounting configuration.

Ground feed was used as the test material in the experiment. Physical properties of the feed are listed in Table 1. The bulk density was calculated by dividing the measured in-bin mass by the feed volume. The moisture content was determined by the air-oven method as recommended in ASAE Standards (ASAE 1998b) for unground grain and seeds. A direct shear apparatus was used to measure the angle of internal friction and cohesion of the feed and the friction angle between the feed and the bin wall. To minimize the time effect on feed behaviour, a low shearing speed of 0.5 mm per minute was used in the direct shear tests. Cohesion was obtained by extrapolating the yield locus to obtain the intercept of the yield line on the plot of shear stress vs normal stress.

A screw auger mounted horizontally over the bin provided a central filling of feed into the bin at a rate of 36 kg/min. Discharged feed was collected in a collection hopper beneath the bin and another screw auger was used to convey the feed into a storage bin. After each test, the storage bin was covered with a plastic sheet to minimize moisture content changes.

Preliminary tests were performed to determine the required settling time for feed en masse to stabilize in the bin after filling. It was found that settling occurred primarily within 30 min after the bin was filled. Therefore, a settling time of 30 min was used in all tests.

Black powder was used to make marking grids in the feed mass so that the flow patterns could be visualised along the front wall of the bin. A grid consisted of four solid lines and four dotted lines with the two adjacent lines 100 mm apart in the hopper section and 300 mm apart in the bin (cylinder) section. Each dotted line consisted of five "dots", spaced 200 mm apart horizontally.

Feed movement in the bin was recorded by a video camera pointing at the front wall. The camera was carefully levelled before each test to avoid image distortion. Video images saved on tapes were then played back on a video cassette recorder (VCR) frame by frame and image frames were digitized and captured by using a video capture board in a microcomputer. To ensure that the time used in the calculation of velocity was correct, a digital quartz timer was placed in front of the bin to calibrate and synchronize the timers of the video camera and the VCR. The differences in time among the three timers were less than 2 seconds within one hour of recording or play back.

Individual image frames were analysed to determine the coordinates of the marking grid lines. From two or more consecutive frames, velocities were calculated for locations where the marking dots were located by:

$$V_x = \frac{X_1 - X_0}{\Delta T} \quad (1)$$

$$V_y = \frac{Y_1 - Y_0}{\Delta T} \quad (2)$$

$$V = \sqrt{V_x^2 + V_y^2} \quad (3)$$

where:

V_x = horizontal velocity component (mm/s),

V_y = vertical velocity component (mm/s),

V = velocity (mm/s),

X_0 = horizontal coordinate of the marking dot in the first image frame (mm),

X_1 = horizontal coordinate of the marking dot in the second image frame (mm),

Y_0 = vertical coordinate of the marking dot in the first image frame (mm),

Y_1 = vertical coordinate of the marking dot in the second image frame (mm), and

ΔT = time interval between the two frames (s).

Lighting played a key role in obtaining high quality images. The arrangements of the light sources were determined by trial and error, i.e., locations of light sources and diffusion directions were adjusted manually and images were recorded and compared. The final arrangement was selected based on the image quality.

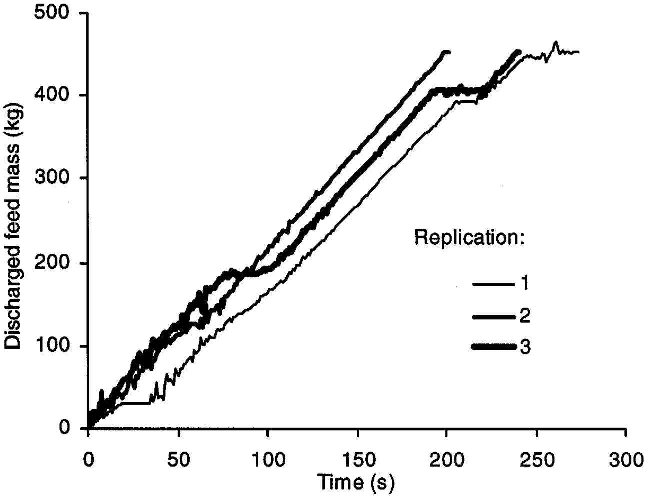

Fig. 2. Feed mass discharged from the bin for test without bin insert.

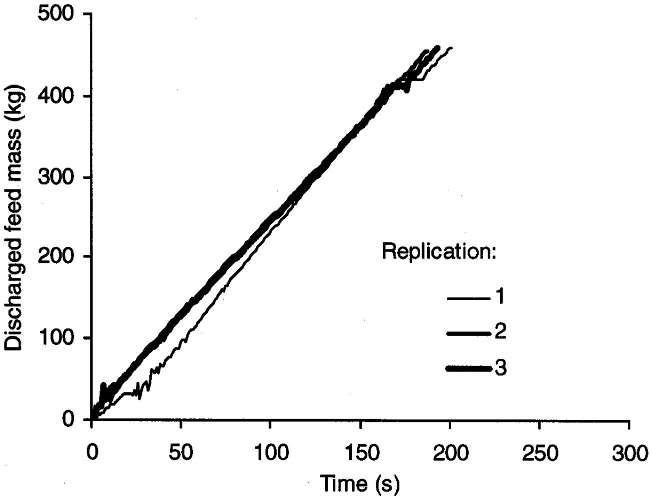

Fig. 3. Feed mass discharged from the bin for test with a fixed bin insert installed at the bin-hopper transition (L/H = 1.00).

RESULTS and DISCUSSION

Discharge rates

When cohesive materials are discharged from storage bins, formation and breakage of arches may cause the discharge rate to fluctuate, or even cause the flow to stop completely. This was clearly indicated by the discharge curves (discharged feed mass vs time) when no insert was installed (Fig. 2). Large variations were observed both within and between test replications. In the first 10 s of discharge, the average discharge rate was 1.97, 3.43, and 3.51 kg/s for the three replicates, respectively. The rate in replicate 1 was significantly lower than those for the other two replicates ($P < 0.05$, degrees of freedom = 29). The first arch occurred at 19 s in test replicate 1 and the total feed mass discharged up to this point was 32.1, 38.2, and 57.5 kg for the three replicates, respectively. There appeared to be a stable discharge period in all three replicates within which the discharge rate varied little (Fig. 2). The stable period occurred between 70 to 210 s, 80 to 200 s, and 105 and 200 s for the three replicates, respectively. The corresponding discharge rates were 2.08, 2.35, and 2.27 kg/s. Although the difference among these three rates was less than that at 10 s, it was statistically significant ($P < 0.05$, degrees of freedom = 284). Compared with no insert tests, feed flow was more consistent when a fixed insert was installed at the bin-hopper transition (Fig. 3). The discharge rate was fairly constant throughout the discharge process. No flow stoppage occurred and small variations between replications were observed. For example, the largest difference in time for emptying the bin was 7 s (5%) among the

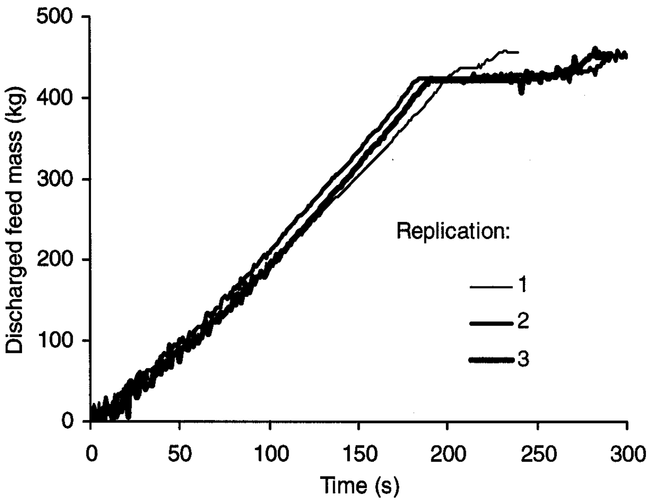

Fig. 4. Feed mass discharged from the bin for tests with a fixed bin insert installed near the discharge outlet (L/H = 0.45).

three replicates, compared with 72 s (36%) for no insert tests. The discharge curves for the mounting locations of L/H=0.70 and 1.70 were similar to that for L/H=1.00, except that bridging occurred in both tests of L/H = 0.70 and 1.70. When the insert was close to the outlet (L/H=0.45), an initial arch had to be broken before feed started to flow and it was difficult to empty the last bit of feed (~6%) from the bin (Fig. 4).

Table 2. Measured overall discharge rates.

	Rate (kg/s) (95% CI)
No insert	1.94 (1.93, 1.96)
Fixed insert at L/H = 0.45	1.87 (1.85, 1.88)
Fixed insert at L/H = 0.70	2.41 (2.41, 2.42)
Fixed insert at L/H = 1.00	2.97 (2.96, 2.98)
Fixed insert at L/H = 1.70	2.27 (2.25, 2.29)
Rotating insert at L/H = 0.70	2.55 (2.51, 2.59)

L = distance from the centre of insert to the discharge outlet
H = hopper height

For each insert mounting configuration, an overall discharge rate was determined as the slope of the discharge curve for the entire discharge period by performing linear regression on data pooled from three replicates (Table 2). When the insert was mounted at the bin-hopper transition (L/H=1.00), the overall discharge rate increased from 1.94 to 2.97 kg/s, or 53%, compared with no insert condition. In contrast, the discharge rate decreased slightly (4%) when the insert was too close to the outlet (L/H=0.45). This indicated that the bin insert improved the discharge rate noticeably when installed properly and the most effective location for installing an insert was near the bin-hopper transition. When the insert was mounted too close to the outlet, it actually became an obstacle to flow because of small gaps between the insert and the hopper wall, thus reducing the discharge rate. Compared with the fixed insert at the same location, the rotating insert mounted at H/L=0.70 produced a slightly higher discharge rate (2.55 vs 2.41 kg/s).

Flow patterns

When no insert was installed, funnel flow occurred at the beginning of discharge and feed flowed out through a centre channel at a relatively high velocity (about 90 mm/s). Due to either bridging or ratholing, flow stopped the first time at 19, 34, and 81 s of discharge in the three replicates, respectively. A typical rathole is shown in Fig. 5 with a width about 17% of the bin width. When the rathole was manually broken, feed collapsed into the channel and bridging occurred above the outlet. After several times of manually breaking bridging, a new flow channel developed, with feed sliding along the free surface and filling in the flowing channel. This flow-arching-manual breaking-flow cycle repeated three times in average before the bin was completely emptied.

Mass flow took place in the bin when the fixed insert was installed at L/H=1.00, except that a short period of funnel flow was observed when the bin was close to empty. At the beginning of discharge, feed in the upper part of the bin moved downward with the material on the left side of the bin moving slightly faster than the right side (Figs. 6 and 7). Two distinct flow channels developed in about 15 s of discharge with a fast channel on the left and slow one on the right. The velocity of feed movement in the fast flowing channel was 2.3 times that in the slow channel (16.3 vs 7.2 mm/s) near the top surface and 2.9 times near the bin-hopper transition (21.4 vs 7.5 mm/s). The differences in flow velocities between the two channels became greater as the flow channels further developed (Fig. 7). Multiple channel flow in a model bin with inserts

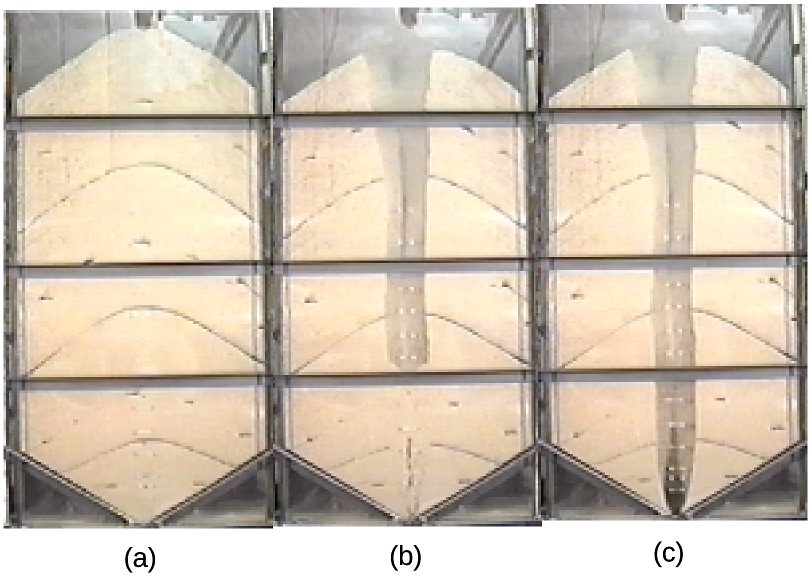
(a) (b) (c)

Fig. 5. Digitized images of feed flow in a test without bin insert. Images taken at: (a) 0 s, (b) 15 s, and (c) 34 s.

was also observed by Zhang et al. (1997), but they did not compare the velocities of material movement between flow channels. The development of two distinct flow channels was caused by the insert. With the insert placed directly above the outlet, feed could not flow in a single central channel towards the outlet. Asymmetric flow was attributed to the fact that the bin system was not perfectly symmetric, e.g., mounting error of insert (slightly off-centre) and variations in feed properties within the bin.

Flow patterns for other insert mounting locations were generally similar to those for the test of L/H =1.00, except that manual breaking of the arch was required to completely empty the bin. When the insert was placed at L/H=0.45, bridging occurred and flow stopped when a small amount of feed between the insert and outlet was emptied out (Fig. 8). This was attributed to small gaps between the insert and the hopper wall when the insert was mounted too close to the outlet. However, feed started to flow in the mass flow mode when the initial bridging was manually broken. Bridging formed again when the bin was close to empty. In three replications, bridging formed twice, in average, before the bin was completely emptied. When the insert was mounted at L/H=0.70, bridging occurred once in one replicate. For mounting location of L/H =1.70, ratholing occurred and flow stopped once before the bin was completely emptied in one replicate. It seemed that the insert placed at a low position produced an obstruction to the flow and the insert became less effective when it was placed too far away from the outlet.

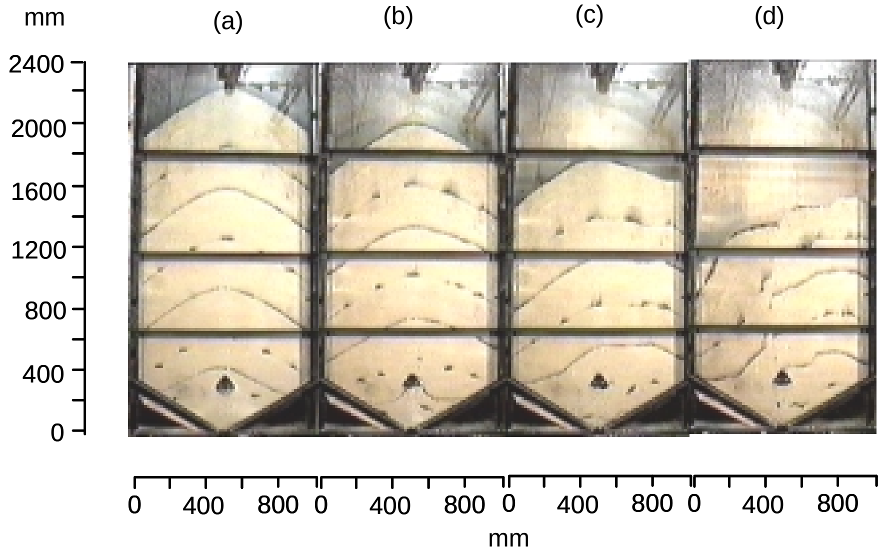

Fig. 6. **Digitized images of feed flow in a test with a fixed bin insert installed at the bin-hopper transition (L/H = 1.00). Images taken at: (a) 0 s, (b) 15 s, (c) 30 s, and (d) 60 s.**

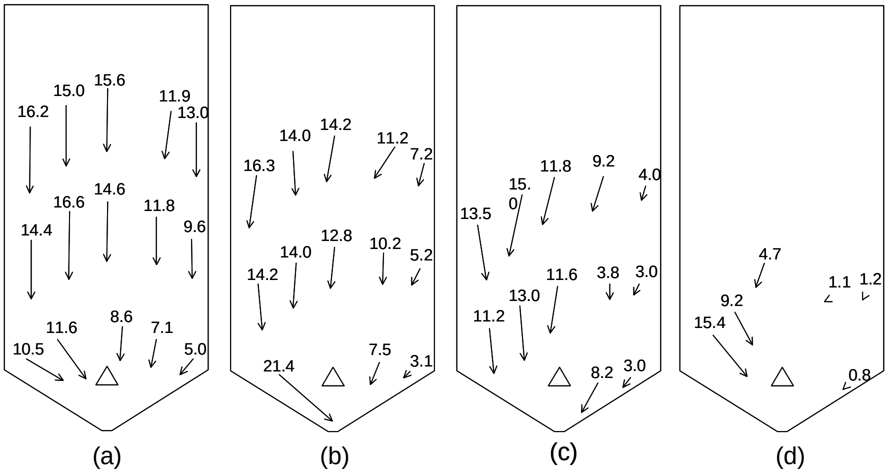

Fig. 7. **Measured average velocities (mm/s) of feed for: (a) 0-15 s, (b) 15-30 s, (c) 30-45 s, and (d) 60-75 s in a test with a fixed bin insert installed at the bin-hopper transition (L/H =1.00).**

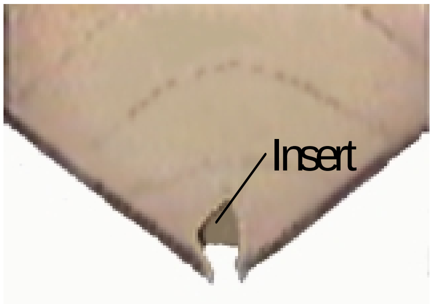

Fig. 8. **Digitized image of feed flow in a test with a fixed bin insert installed near the discharge outlet (L/H = 0.45).**

Mass flow occurred in the bin when the rotating insert was installed at L/H=0.70. Similar to the fixed insert, the rotating insert divided flow into two flow channels, a fast flowing channel on the left and slow one on the right (Fig. 9), but the differences in velocities between the two channels were greater than those for the fixed insert. It seemed that the rotating insert was more effective in breaking arching than the fixed insert mounted at the same height because no flow stoppage occurred in tests with the rotating insert at 70% of hopper height. Viewing the recorded video images in slow motion revealed that the insert oscillated in a range of ±2° during discharge. This oscillating motion helped break arches.

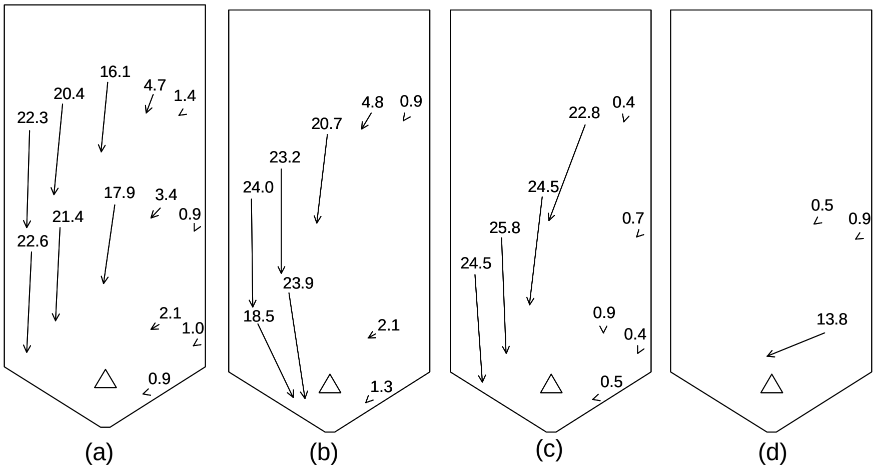

Fig. 9. Measured average velocities (mm/s) of feed for : (a) 0-15 s, (b) 15-30 s, (c) 30-45 s, and (d) 60-75 s in a test with a rotating bin insert installed at L/H = 0.70.

CONCLUSIONS

1. Discharge of cohesive feed from the model bin was more consistent when a bin insert was installed. The bin insert increased the discharge rate noticeably (53%) when installed at the bin-hopper transition. When the insert was placed close to the outlet (at 45% of hopper height), it became an obstacle to the flow and reduced the discharge rate slightly (4%).
2. The bin insert changed the feed flow from funnel to mass flow mode in the model bin. The insert divided flow into two distinct flow channels. The flow channels were generally asymmetric and velocity differences between the two channels increased as the flow channels further developed.
3. The insert was more effective in preventing the formation of arches when it was installed at the bin-hopper transition than other locations. The rotating insert was more effective than the fixed insert in reducing arching because of the oscillating motion of the insert caused by the flowing material.

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