The Use of Standpipes for Increasing Limiting Gravitational Flowrate from Mass Flow Bins

Z.H. Gu, P.C. Arnold and A.G. McLean
Department of Mechanical Engineering
The University of Wollongong

Abstract

This paper provides an experimental and theoretical examination of the use of standpipes to increase the limiting flowrate by gravity from mass flow bins. The results indicate that the effect of a standpipe attached under the hopper outlet is greater as the particle size becomes smaller and the length of the standpipe becomes longer, provided the standpipe remains full of solids.

1. Introduction

It is recognized that the flowrate of fine powder from mass flow bins can be orders of magnitude less than the flowrate obtainable for coarse powders. It is clear that the limiting flowrate of fine material mainly is caused by the self-generated negative air pressure gradient at the outlet of a bin. Therefore, one of the most important strategies for increasing the limiting flowrate is to reduce the interstitial pressure gradient, especially that at the outlet. There are various possibilities to achieve this improvement in flowrate, such as reducing the surcharge level, air permeation techniques, and the use of a standpipe. Of these possibilities, the use of a standpipe, which can assist in increasing the flowrate of fine powders without reducing the storage capacity in the bin (as in reducing the surcharge level) or requiring a low pressure supply of high quality air (as in air permeation), is a practical technique applying to industrial problems. The simple addition of a vertical non-converging pipe to the bottom of an existing mass-flow hopper produces a pressure gradient in the standpipe and creates a vacuum at the hopper outlet. This suction effect substantially increases the flowrate of bulk solids from the hopper, as found in many research studies. Ginestra et al. and Chen et al. studied a very long standpipe with the ratio between standpipe length and diameter being more than 100. This kind of long standpipe is not applicable in industry for the purpose of increasing the flowrate of bulk solids from bins, due to headroom restrictions. Hence, some work needs to be done to study the extent to which the flowrate is increased by a standpipe with a limited length. In this paper some experimental observations and a pilot theoretical investigation on the flow of bulk solid from a mass flow bin and standpipe configuration are reported.

2. Experiments and observations on standpipes

2.1 Test Apparatus

The experiments were carried out on a modified double-bin apparatus; a standpipe was installed at the outlet of the test bin of the double-bin apparatus, as shown in Fig. 1. The standpipes used in the experiments had length-to-diameter ratios (L/D₀) of 1, 2, 3, 4, 5 and 10 (D₀ = 0.0445 m). The joint between the standpipe and the outlet of the hopper was sealed to avoid air leakage. A belt feeder was only used for the longer test standpipes (L/D₀ = 5, 10) to obtain a steady flowrate. A chart recorder was used to record the mass variation in the bin-standpipe configuration versus discharge time. The flowrate was calculated by differentiating the mass curve with respect to time.
2.2 Experimental Observations

i) Attainable Flowrate by Using the Standpipe

Observations were made on the flowrate improvement attainable using alumina as the bulk solid. Fig. 2 summarizes the results. Generally, the flowrate increased with the length of the standpipe. Specifically, as the standpipe length increased the flowrate increased slowly at first then at a faster rate. For instance, a short standpipe \((L/D_0 = 1\) and 2) increased the flowrate by less than 20\% while the standpipe with \(L/D_0 = 5\) provided an increase in flowrate of 200\% for the alumina. However, as the standpipe became longer, the flowrate did not continue to increase at this rate. Actually, the rate of the increase in flowrate reduced, e.g., the flowrate increased by 300\% for the standpipe with \(L/D_0 = 10\).

ii) Problems When Using a Standpipe

As the higher flowrates were approached with the long standpipe, fluctuations in the flowrate were observed. These fluctuations are explainable by two typical discharge modes observed for material flowing through the standpipe: in one mode the standpipe was partially filled with the bulk solids, while in the other mode the standpipe was filled fully with the solids. The higher flowrate occurred only as long as the standpipe was full of material; in this situation the bulk solid discharging from the standpipe effectively entrains the air in the voids between particles inducing an efficient suction on the particle flow from the hopper. For a partially filled standpipe this suction is not generated as effectively resulting in a lower flowrate. The transition state between these two flow modes resulted in flow instability. Matsen\(^{10}\) suggested that this instability is caused by a bubble held stationary in the standpipe. Instability of the flow is a common phenomenon when using a standpipe. The same problems have been also reported by Johanson\(^9\) and Leung et al.\(^{11,12}\). In addition a jump phenomenon has been reported by Chen et al.\(^7\) between the upper and the lower bound flowrate in some situations, with the actual bounds differing by an order of magnitude.

To reduce the extent of these fluctuations and to ensure that the standpipe remained full at all times a belt feeder was installed under the standpipe. With the belt feeder installed, the maximum steady flow rate attained, using the standpipe of \(L/D_0 = 5\), was 0.728 kg/sec (Fig. 3), which represents 97.4\% of the maximum attainable flowrate for discharge from this test bin. As Johanson\(^9\) pointed out, it is essential that the feeder controls the flow slightly below the limiting rate as the higher flowrate occurs only as long as the standpipe remains full of solids.

![Fig. 1 Standpipe installed at the outlet of the test bin.](image)

![Fig. 2 Flowrate vs. \(L/D_0\) ratio of standpipe for alumina (Surcharge level \(H = 0.31\) m).](image)

![Fig. 3 Flowrate vs. feeder belt velocity for different clearances between feeder and standpipe \((L/D_0 = 5)\).](image)
For a short standpipe, e.g., L/D₀ = 1, a significant increase in flowrate cannot be obtained. This is due to the low suction effect generated or even, in most cases, an ineffective suction due to the boundary effect (the outlet of the standpipe is close to the hopper outlet).

3. Modelling the flowrate of bulk solids from a bin-standpipe configuration

A theoretical model, based on the model developed by Gu et al.¹³,¹⁴ for predicting the pressure gradients and the flowrate of bulk solids, has been established to explain the experimental observations for the standpipe.

In this model the geometry of the mass flow bin with a standpipe installed is divided into four regions, as shown in Fig. 4.

![Fig. 4 Four regions for bin-standpipe configuration](image)

The assumptions used are as follows:

i. The bulk solid and interstitial air flows are continuous so that the model presented can be based on continuum mechanics theory. The flowrates of particles and air at any cross-section in a mass flow bin are constant.

ii. The dynamic deaeration at the top surface of bulk material is proportional to the flowrate of particles.

iii. The principal stresses are assumed to be vertical in region I, radial in region III while the region II is regarded as a transitional region. The standpipe remains dull of bulk solid with the stress distribution in region IV being linear with respect to height.

iv. The walls of the hopper and the standpipe are smooth so that the effect of wall friction can be disregarded.

v. The location of the minimum interstitial air pressure for the bin-standpipe configuration (hₘₓ/ₜₚ) is in the hopper section between hₘₓ and h₀ for a standpipe with a limited length. The effective suction induced by the standpipe is assumed to be dependent on the length of the standpipe.

\[
(\eta_{ₘₚ})_{ₚ} = \eta_0 \left( 1 + \frac{\eta_{ₘₓ} - \eta_0}{1 + \eta_0} \right) e^{-\frac{\lambda L}{D₀}}
\]  

where

\[
\lambda = \text{standpipe effect coefficient; } (0 < \lambda < 1).
\]

\[
\eta = \frac{h}{h₀} \text{ for all the relevant subscripts depicted in Fig. 4.}
\]

The assumption v. does not allow the minimum interstitial air pressure to be located in the standpipe section and, consequently, to induce a flowrate greater than that possible without any negative air pressure effect. It is believed that this assumption is reasonable for standpipes with limited length, however, the location of the minimum interstitial air pressure in the standpipe section is possible with longer standpipes.

Considering the above assumptions, the air pressure gradient at the hopper outlet for the bin-standpipe configuration will be evaluated in a similar way to that in Gu et al.¹³ while the flowrate of bulk solid will be predicted by the flowrate model in Gu et al.¹⁴. By adopting these models the following quadratic equation, for predicting the flowrate of bulk solid from the bin-standpipe configuration, is obtained:

\[
q_1 Q_p^2 + q_2 Q_p - g = 0
\]  

where the first term represents the inertial force of flowing bulk solid; the second term evaluates the resistance to flow caused by the interstitial air pressure gradient and the third term evaluates the effect of the body force due to gravity. The coefficients q₁ and q₂ are determined by the flow properties of the bulk solid (bulk density constants - \(ρ_0\), \(b_1\), \(b_2\)¹⁵), permeability constants - \(C_0\), \(α\)¹⁶, internal friction angle of the bulk solid \(δ\), the geometry of the bin-standpipe configuration (the hopper half angle \(α\), the diameter of outlet \(D₀\), the diameter of the vertical bin section \(D\), and the length of the standpipe \(L\)) and the extent of material storage in the bin (material surcharge level \(H\)).
4. Theoretical predictions and discussion

To verify this theoretical model, the flowrates of alumina flowing from the test bin with a 0.0445 m outlet have been predicted and compared with the observed flowrates. A comparison of the theoretical results with the experimental results, for a sequence of fixed values of the coefficient $A$, is depicted in Fig. 5. The value of $A = 0$ implies no effect of the standpipe on the minimum pressure position.

The comparison indicates that the predicted flowrate increases with increase in standpipe length, although for the standpipe with a lower $L/D_0$ ratio the theoretical results are over-predicted. The over-prediction of the flowrate at lower $L/D_0$ ratio may be caused by a different flow mode in the standpipe. In particular the theoretical results are based on the assumption of the standpipe being completely filled with solids. As the belt feeder was only used in the experiments with the long standpipe ($L/D_0 = 5$), it may be possible that the "standpipe-full" condition for the lower $L/D_0$ ratio standpipes did not match the assumption. Hence a lower suction effect may have occurred in the experimental standpipe mentioned in Section 2.2.

The predicted and measured flowrates depicted in Fig. 5 lie between the flowrate bounds calculated assuming maximum negative air pressure gradient at the hopper outlet (lower bound) and no air pressure gradient at the hopper outlet (upper bound). This confirms that the location of the minimum interstitial air pressure is in the hopper section for a standpipe with a limited length and it is affected by the length of the standpipe. For the results obtained in Fig. 5, it seems that $\lambda = 0 - 0.05$ as $L/D_0 \leq 4$ and $\lambda = 0.75$ as $L/D_0 \geq 5$, although further systematic work is required before reaching a general conclusion. For the moment, the further discussion is based on the results for the case of $\lambda = 0.75$.

The theoretical model can be used to predict the effect of material permeability on the flowrate from a bin standpipe configuration. In particular this effect can be quantified by defining an enhancement factor $F_{sp}$ as the ratio of the flowrate with a standpipe to that without a standpipe. Fig. 6 shows the calculated variations of enhancement factor $F_{sp}$ with $L/D_0$ ratio for alumina, Sand MD2 and Sand M1, which have the permeability constants 398, 1054 and 6518*10$^{-9}$ (M$^4$N$^{-1}$Sec$^{-1}$) respectively. The variations depicted in Fig. 6 clearly indicate that a standpipe can create a higher flowrate enhancement for finer bulk solids than for coarse materials. Specifically, the flowrate enhancement factors produced by a standpipe with $L/D_0 = 7$ are 4, 2 and 1.06 for alumina, Sand MD2 and Sand M1 respectively. These results coincide with other researchers' results, as illustrated in Table 1, indicating that the use of a standpipe increases the flowrate more effectively for fine material than for coarse material.

![Fig. 5 Predictions of flowrate vs. $L/D_0$ ratio](image1)

![Fig. 6 Enhancement factor for different materials](image2)

The increase in flowrate using the standpipe is caused by the vacuum suction at the hopper outlet and a reduction of the negative air pressure gradient. This is evident from Fig. 7 and Fig. 8 which show the variations of predicted air pressure and air pressure gradients at the hopper outlet for the fine and coarse materials.
Table 1 A summary of the results in using standpipes

| Researcher | Material used (Particle size or permeability constant) | Diameter of standpipe | Dimensionless length of standpipe | Enhancement factor |
|------------|--------------------------------------------------------|-----------------------|-----------------------------------|-------------------|
| Chen et al. in 1984 | Fine sand \(d_{50} = 154 \mu m\) | 0.0254 | 130 | 8 |
| (Experimental results) | Coarse sand \(d_{50} = 556 \mu m\) | | | 2.5 |
| Ginestra et al. in 1980 | Unnamed material \(\delta = 30^\circ\) | 0.030 | 100 | 7 – 8 |
| (Predicted results) | \(V_t = 0.1 \text{ m/sec.}\) | | | |
| Knowlton et al. in 1986 | Sand \(53 - 177 \mu m\) | 0.038 | 185 | 6.4/5.6 |
| (Measured/predicted) | Sand \(177 - 420 \mu m\) | | | 4.6/5.3 |
| | Sand \(420 - 840 \mu m\) | | | 3.3/3.6 |
| Yuasa et al. in 1972 | Glass beads \(d_{50} = 127 \mu m\) | 0.0091 | 165 | 5.9 |
| (Measured results) | Glass beads \(d_{50} = 254 \mu m\) | | | 3.25 |
| | Glass beads \(d_{50} = 505 \mu m\) | | | 2.11 |
| | Glass beads \(d_{50} = 1015 \mu m\) | | | 1.5 |
| Current experimental results | Alumina \(d_{50} = 100 \mu m\) \((C_0=398.38)^*\) | 0.0445 | 5 | 3.14 |
| Predicted results by current model | Alumina \(d_{50} = 100 \mu m\) \((C_0=398.38)^*\) | 0.0445 | 7 | 4 |
| | Sand MD2 \(d_{50} = 200 \mu m\) \((C_0=1054.4)^*\) | | | 2 |
| | Sand M1 \(d_{25} = 310 \mu m\) \((C_0=6517.5)^*\) | | | 1.06 |

* permeability constant \(C_0 \times 10^{-9} \text{ m}^2 \text{ N}^{-1} \text{ s}^{-2}\)

material alumina and coarse material Sand M1, respectively. Corresponding to these results, Figs. 9 and 10 show the air pressure distributions in the bin and standpipe generated by alumina and Sand M1 respectively.

From Fig. 9 and Fig. 10 it can be seen that the predicted air pressure distribution in the standpipe is a linear function of the depth for short standpipes, while it is a nonlinear variation for long standpipes.

In contrast, Yuasa et al.\(^3\), Chen et al.\(^7\) and Knowlton et al.\(^8\) observed an almost linear relationship between negative air pressure and the depth in the standpipe in most of their experiments. The nonlinear relation produced by the current model may be caused by the constraint of the minimum air pressure position within the hopper section. Indeed, for a very long standpipe, the experimental results obtained by Yuasa et al., Chen et al. and Knowlton et al. (for standpipes
Coarse sand (Sand M1)

Fine material (alumina)

\[
\text{Fig. 8 Predicted air pressure gradient at hopper outlet}
\]

\[
\text{Fig. 9 Predicted air pressure distributions in the bin and the standpipe for alumina.}
\]

\[
\text{Fig. 10 Predicted air pressure distributions in the bin and the standpipe for sand M1.}
\]

\[
\text{of L/D_0 \geq 100) show the occurrence of the minimum air pressure below the hopper outlet. In this case, a higher flowrate can, theoretically, be produced by the standpipe since the positive air pressure gradient developed at the hopper outlet accelerates the particle flow.}
\]

\[
\text{5. Concluding remarks}
\]

The use of standpipes to increase the limiting flowrate by gravity was examined both theoretically and experimentally. The results indicate that

- the use of standpipes can increase the flowrate significantly for fine particles (lower permeability materials) and insignificantly for coarse particles (higher permeability materials);

- The longer the standpipe, the more significant the suction effect induced by the standpipe and the higher the flowrate that can be obtained. However, the rate of increase in flowrate due to the suction effect is not proportional to the length of standpipe with three different periods being apparent, as the length of standpipe increases. This suggests that

  i) a standpipe with a length limited by practical constraints, can be efficiently used for increasing the flowrate;

  ii) the flowrate enhancement to be gained by using standpipes with very large L/D_0 ratios may not warrant the extra headroom required.

A standpipe is only efficient when it is kept full of bulk solid. This suggests that some precaution needs being taken to ensure that the standpipe remains full, for instance, by using a feeder under the standpipe outlet to control the flowrate. There seems to be an optimal standpipe L/D_0 value to achieve beneficial flowrate enhancement and the prediction of this optimal value needs further investigation.

\[
\text{Nomenclature}
\]

\[
\begin{align*}
a & : \text{exponent used to relate permeability to consolidation stress} \\
b_1, b_2 & : \text{constants in consolidation-related bulk density equation models} \\
C_0 & : \text{bulk solid permeability at lowest compaction, } *10^{-9}(\text{m}^4\text{N}^{-1}\text{s}^{-1}) \\
d_{50} & : \text{median particle size (\text{\mu m})} \\
D & : \text{diameter of vertical section of the bin (m)} \\
D_0 & : \text{outlet diameter of the hopper, diameter of the standpipe (m)} \\
F_{sp} & : \text{flowrate enhancement factor due to the use of standpipe (-)} \\
g & : \text{gravitational acceleration (m/s}^2) \\
h & : \text{vertical distance measured from vertex of hopper (m)} \\
h_0 & : \text{vertical distance from vertex of hopper to outlet hopper (m)} \\
h_1 & : \text{vertical distance from vertex of hopper to transition of a hopper (m)} \\
h_{osp} & : \text{vertical distance from vertex of hopper to outlet of standpipe (m)} \\
h_{mp} & : \text{vertical distance from vertex of hopper to minimum pressure position - no standpipe case (m)}
\end{align*}
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