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Material Flow Characteristics Within A Silo

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The flow within a silo is classified as one of the following:

1. **Mass Flow**
   Mass flow is defined as a flow that develops in a silo when all the stored material in the silo is in motion whenever any material is withdrawn from the silo. This is referred to as "first in, first out" flow.

2. **Funnel Flow**
   Funnel flow is defined as a flow that develops in a silo when some material in the silo center column moves while some material next to the silo inner walls remains stationary. This type of flow develops due to the shallow angle of the silo hopper or due to the rough surfaces of the silo hopper. This flow pattern is referred to as "first in, last out".

3. **Expanded Flow**
   Expanded flow is defined as a flow that combines the mass flow and funnel flow, and consists of a mass flow at the silo hopper, expanding up to a larger diameter to prevent formation of a rat hole. Above this mass flow section, the silo is designed for a funnel flow pattern. (1)

   This flow pattern allows the use of a funnel flow and a mass flow, and reduces the overall height of the silo by allowing us to increase the diameter of the silo.

   It is not recommended to use an expanded flow design for silos that are less than 25' diameter. It is not cost effective. (4)

There are several factors that affect the flow of material within the silo. The following are the most important factors:

a. **Adhesive and Cohesive Strength of Material**
b. **Compressibility of Material**
c. **Silo Wall Friction (Plus Abrasive Nature of Material)**
   - **Static Friction**
   - **Dynamic Friction**
d. **Material Size**
e. **Material Moisture**
f. **Bulk Density of Material**

In the following paragraphs, I will discuss each of the above factors and how they impact the flow of material within the silo.

a. **Adhesive and Cohesive Strength of Material**
Adhesive strength of material refers to the quality of material that makes the particles stick together. This is a surface characteristic and negatively affects the flow of material. The finer the particle size of the adhesive material, the stronger the adhesion strength and vice versa. Cohesive strength is the characteristic of material that is defined as molecular attraction that holds the fine particles together. Material with high cohesive strength will have a tendency to hinder the flow and cause bridging and/or ratholling.

Kaolin powder is a good example of material with high adhesive strength. The material with high adhesive strength will bridge in the silo. Hydrated lime powder is another example of material that would bridge in the silo.

b. **Compressibility of Material**
Compressibility is defined by the following formula:

$$C\ (\%) = \frac{100\ (P-A)}{P} \quad ^{(2)}$$

C = Compressibility
P = Packed bulk density
A = Aerated bulk density

Compressibility is affected by material cohesion and moisture content. The more compressible the material, the less flowable the material and vice versa. In general, powders are more compressible than granular material.

c. **Silo Wall Friction (Material Abrasiveness)**
The silo wall friction against the material not only will affect the flow of material but also depending on the abrasiveness of material will cause wear in the silo wall and discharge cone of the silo.

To minimize wall friction, the inner surfaces of the silo wall must be smooth and free of obstructions. A “2B” finish is highly desirable particularly on the inner surface of the silo discharge cone. There are two kinds of wall frictions:

- Static friction
- Dynamic friction

Static friction is the friction of material in contact with the silo wall when material is not moving. Once the material is moving, the friction between the material and bin walls is called dynamic friction. The lower the wall friction and lower material abrasiveness, the better the material flow **mass flow**; the higher wall friction, the less material flow next to the silo wall thus **funnel flow**.

Since static friction is greater than moving friction, stopping and starting the flow of material out of the silo will cause bridging particularly in a powdery material.

d. **Material Particle Size and Shape**
Material particle size affects the flow of material out of the silo more than any other factor. In general, granular materials flow better than powders. However, as the material size gets larger and material shape gets more irregular, the material flow is adversely affected.

For example, pebble lime flows much better than powder hydrated lime. Once the particle size increases to 2” or larger, the flow becomes more troublesome. Round particles flow much better than irregular shape particles.

For the sake of clarity we define material size in this paper as follows:

Powders = 100 mesh and smaller
Granular = 10 to 100 mesh
Pebbles = ¼” to ¾”

These classifications are only to give the reader some idea of the size of material and are not intended to be used as standard definitions.

e. **Material Moisture**
The impact of moisture on material flow in the silo depends on several factors:

- Absorbed moisture
- Surface moisture
- Particle size of material
- Percent of moisture content

Materials such as hydrated lime powder and bottom ash powder are extremely susceptible to moisture. Moisture makes these materials form clumps and not flow at all. It should be noted that absorbed moisture not molecular moisture content affects the flow of material.

Surface moisture generally forms on the surface of material such as limestone particles. This water will not be absorbed by the material and remains on the surface. If the material size is ¼” or larger, surface moisture up to 6% to 7% will not affect the flow of material.

f. **Bulk Density of Material**
Bulk density is defined as the weight of material per cubic foot. There are three kinds of bulk density:

- Compacted density
- Aerated density
- Working or dynamic density

Working density is calculated by the following formula:

$$W = (P\text{-}A)C+A \quad {}^{(2)}$$

W = Working density
P = Packed density
A = Aerated density
C = Compressibility

Compressibility is the relation between packed density and aerated density. It is calculated by the following formula:

C is in percentage

$$C = \frac{100(P\text{-}A)}{P} \quad {}^{(2)}$$

EXAMPLE
Assume a material with the following characteristics:

(P) Compacted density 25#/ft^3
(A) Aerated density 15#/ft^3

$$\text{Compressibility } C = \frac{100(P\text{-}A)}{P}$$

$$C = \frac{100(25\text{-}15)}{25} = 40\%$$

$$\text{(W) Working Density} = (P\text{-}A)\ C+A$$

$$W = (25\text{-}15)\ \frac{40}{100} + 15 = 19{\neq}/ft^3$$

In general, the higher the compressibility of material, the less flowable the material and vice versa.

For highly compressible material, it is advisable to avoid very tall silos. Tall silos require some type of flow aid such as fluidization.

Silo Design

Before designing the silo geometry, it should be determined what type of flow is required in the silo; mass flow or funnel flow.

In most cases, a mass flow is preferable. To achieve a mass flow with a particular material, the following conditions must be present:

- Material should be flowable
- Material should have low compressibility
- Material should have low adhesive and cohesive strength
- Silo straight walls interior must be smooth
- Silo discharge cone should have a 70° minimum angle to horizontal and the cone internal surfaces should be “2B” finish.
- Discharge diameter must be large enough for material flow.

Funnel flow can be used when:

1. Opening in the silo discharge is large enough to prevent rat holing
2. A first in last out flow is acceptable
3. Material does not degrade with time
4. Particle segregation is not of concern

Multiple outlet silos are always funnel flow.

Determining the Size of Silo Outlet

To determine the minimum size of a circular outlet for a mass flow silo, the rule of thumb is that the minimum outlet diameter must be 6 to 7 times the diameter of the largest particle of material in the silo.

To determine the maximum flow of material out of a silo through a circular discharge, the following formula is used for coarse free flowing material:

$$Q = \tau A \sqrt{\frac{Bg}{2(1+M)TANG}} \quad (3)$$

where Q is feed rate pounds/second

τ = Bulk density of solid
A = Cross section area of outlet
B = Diameter of circular outlet
G = Acceleration = 32.17 ft/sec/sec
M = 1 for circular outlet
TANG = Tangent of hopper angle

EXAMPLE

Assuming the following:

- Hopper outlet size - 8” diameter or 0.667 ft
- Material bulk density - $55\#/ft^3$
- Material - granular and free flowing
- Output discharge area - 50.24 sq in or 0.349 sq ft
- Hopper angle to vertical - 30°
- Tangent of 30° = 0.5773
- G acceleration = 32.17 ft/sec to calculate the maximum feed rate from the 8” discharge

$$Q = \tau A \sqrt{\frac{Bg}{2(1+M)TANG}}$$

$$M = 1 \text{ for round discharge}$$

$$Q = 55 \text{ X } 0.349 \sqrt{\frac{0.667 \text{ X } 32.17}{2(1+1)0.5773}}$$

$$= 19.2 \sqrt{\frac{21.457}{2.309}}$$

$$= 19.2 \text{ X } 3.084$$

Q = 59.2 lbs/sec maximum feed rate

A coarse solid and fine powder solid of the same bulk density flow differently. Coarse solid free flowing will flow several times that of a fine powder.

With hard to flow material in powder form, fluidization with dry air is the most effective flow aid. However, to prevent flooding through the hopper outlet, a positive displacement feeder must be used at the discharge of the silo hopper.

For easy-to-flow material in granules or pebble form, a vibratory bin discharger is an effective flow aid at the silo discharge. The bin activator diameter is to be 1/3 diameter of the silo for very flowable pebble material and ½ diameter for finer material.

References

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