# HANDLING OF SOLIDS – TRANSPORT AND STORAGE

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## Contents

**Summary**

Bulk solids handling is the science of storing and transporting bulk solids. This chapter presents a perspective of the history, the science and the technological challenges of bulk solids handling. To understand bulk solids one first has to overcome a frequent misunderstanding: Bulk solids are NOT like liquids. Instead they form a separate entity between solids and liquids, dominated by the disperse characteristics of the bulk. The major tools to characterize bulk solids are the particle properties like particle size distribution or particle shape identifiers and the proper bulk characteristics like the bulk solids density and the flow properties.

The particular nature of bulk solids becomes most apparent in the design of storage containers; while tanks for liquids are wide and squat, silos for bulk solids are high and slender, since the maximum stress in the silo fill scales with the diameter, not the height of the vessel. Specific design rules as proposed by Jenike are presented in the chapter, as well as a short overview of the most recent standards on the design of silos for strength.

A specific feature of bulk solids is their capability to cake, i.e. to gain strength during storage at rest. The main physical mechanisms causing this deterioration of a powder flowability is the movement of moisture in the bulk and the formation of crystal bridges at the particle contacts. This problem may be addressed additives, which suppress the caking propensity, or by specific handling strategies (e.g. reducing the time at rest).

Of the many modes of transport of bulk solids only two are being presented in this chapter: pneumatic conveying and screw conveyors. Pneumatic conveying is widely used for mid-range conveying, while screw conveyors dominate the short range, in plant feeding and conveying situations.

## 1. Introduction

Bulk solids handling, its transport and storage, is an often neglected area in many industrial and academic settings. This may have many reasons, not the least are that everybody has had some experience handling bulk solids in kitchen and sandbox since childhood. Also the importance of bulk solids handling in the value generation process is often not understood. Many people just see that the need to handle bulk solids adds cost while not providing an obvious value added. However, neglecting bulk solids handling can quickly destroy all the value of a product, if e.g. it is caked in a silo and has to be washed out to restart operations. The scale of operating problems that can arise in solids handling is also quite unrelated to the capital cost of the equipment concerned. Commissioning over-runs, downtime, production losses and rectification costs can incur horrendous penalties for poor design.

Bulk solids handling is an old, maybe the oldest discipline of chemical process engineering. Nevertheless, it has never achieved the status of a *Unit Operation*. This chapter will provide a short historical overview of the science of bulk solids handling.

The scope of bulk solids handling is very wide, although it "only" deals with shifting bulk solids through space and time. The latter is usually called "storage", the former "transportation". In both situation bulk solids often behave counter-intuitively, at least when one's intuition is based on experience with fluids and gases.

When a steel ball is placed on the bottom of a container with sand and the container is then vibrated, the ball will start to rise to the surface. The same sand, however, will not support a steel ball placed on its surface, if incipiently fluidized by gas percolating through it. Lawrence of Arabia described such effects in reports of "dry quicksand" swallowing entire men. Fine powders, that have flow characteristics similar to a liquid when agitated, tend to settle to a very difficult flow condition when settled.

Bulk solids can be stored either loose or contained. Loose storage is mainly held in stockpiles, but since stockpiles are rather infrequent in Chemical Engineering, they will not be considered in detail. Nevertheless stockpiles may handle the greatest mass, (in tonnage), of all bulk storage operations. The minerals, coal and mining industries rely heavily on this simple form of storing bulk solids. The stacking and reclaiming equipment used to move the vast quantities of material handled in these operations is huge and sophisticated. The Port of Newcastle in Australia ships more than 10.000 Te/h through coal stockpiles along the Hunter River.

Silos range from small, transportable metal containers to the huge grain elevators at Thunder Bay on Lake Superior, where grain from the Canadian plains is loaded on sea going vessels for export. While being deceptively simple in design, they pose significant problems to the process engineer as well as to the civil engineer. Even today silos fail structurally at a rate thousand fold above that of other high rising buildings. From Ed Merrow we know that problems handling bulk solids are also the most common cause of delayed plant start up in the Chemical Industries and that production efficiencies in plant handling loose solids lag well behind those handling liquids and gases.

Bulk solids may be transported by any vehicle ever designed by mankind. The most well known are surely the huge sea going bulk carriers shipping e.g. coal from Australia to Japan and the equally fascinating, virtually endlessly long freight trains transporting goods through the American plains. The other end of the size scale may be seen during our weekly visit to the local grocery, where we buy bulk foods packaged in cardboard boxes or plastic bags. Within the scope of Chemical Engineering the transport of packaged bulk goods provides a lesser challenge. The more significant transport technologies are continuous conveying operations in-plant or across country. Belt conveyers are known to run 6 m wide over hundreds of kilometers transporting bauxite or iron ore. Pneumatic conveying systems and screw conveyors are the workhorses for in-plant conveying. Both provide the benefits of being an enclosed system, and therefore easily adapted to deal with potentially hazardous substances.

It is not usually intended to change the material handled or stored in bulk solids handling. It does happen unintentionally, nevertheless. Depending on the applications and the product this may lead to explosion hazards and/or quality problems in downstream processing. During transportation the particles get stressed and collide with the wall of the equipment and other particles. This leads to particle attrition and the generation of fines. During storage many bulk materials tend to go through a caking process and solidify in the silo or package. While this may be acceptable in a 250 gr. box of powdered sugar, it poses major problems in a silo holding 2000 tons of sugar.

## 2. History

Bulk solids handling is at least as old as the first permanent settlements of men after the Neolithic revolution, when mankind began to farm the land and store the produce instead of just hunting and gathering. Maybe it is even older than that. The first picture of bulk solids storage facilities is from Egypt about 4000 BC. It shows top unloading silos for grain which were dug into the ground of the Nile valley. In contrast to simple storage pits, these silos were big enough to require a specific bucket and elevator system for reclaiming the stored grain.

The history of bulk solids handling as a scientific discipline is much younger, starting only in the 19$^{th}$ century with the work of *Coulomb*, *Rankine* and *Reynolds* who discovered the frictional properties and the dilation behavior of sand while working on civil engineering problems concerning road and dam building. Until today the interdisciplinary work between civil and process engineers has remained a major driving force of development in bulk solids handling. The most important of the early technical papers was published in 1895 by *H.A. Janssen*, a port engineer from Bremen, Germany who looked at the pressure developed in grain storage silos. His formula remains the basis of all but the French standards on stresses in silos, see Section 4.2. Over the following thirty years many aspects of bulk solids storage were investigated, mainly by groups in England and North America, covering e.g. numerical methods, eccentric discharge, non-symmetrical silo-shapes.

The second large wave of scientific advancement started in the 1950's/1960's and is connected with three names: *Roscoe* developed the concept of critical state, which today is the basis of all flow property measurements, see Section 3.2; *Jenike* developed a method of designing silos for flow based of shear tests and the concept of mass flow and funnel flow; *Roberts* started scientific work on the process engineering aspects of screw and belt conveying. Figure 1 shows a time ray of the work mentioned.

New numerical methods became available in the 1980's and were applied to bulk solids handling. The decisive work on Finite Element Methods for silo problems was published by *Eibl* and *Häussler* in 1984. In the same year *Cundall* and *Strack* published their groundbreaking paper on discrete elements in the area of civil engineering.

While Jenike developed the method of shear testing for the design of silos in the 1960's it took almost 30 years for the first quasi-standard on this subject to be published by the EFCE (European Federation of Chemical Engineering) which later spawned many other standards e.g. by BCR of Brussels or the American ASTM. Today most of the knowledge on stresses in silos is made available to structural engineers through the new Eurocode 1991-4, published in 2004.

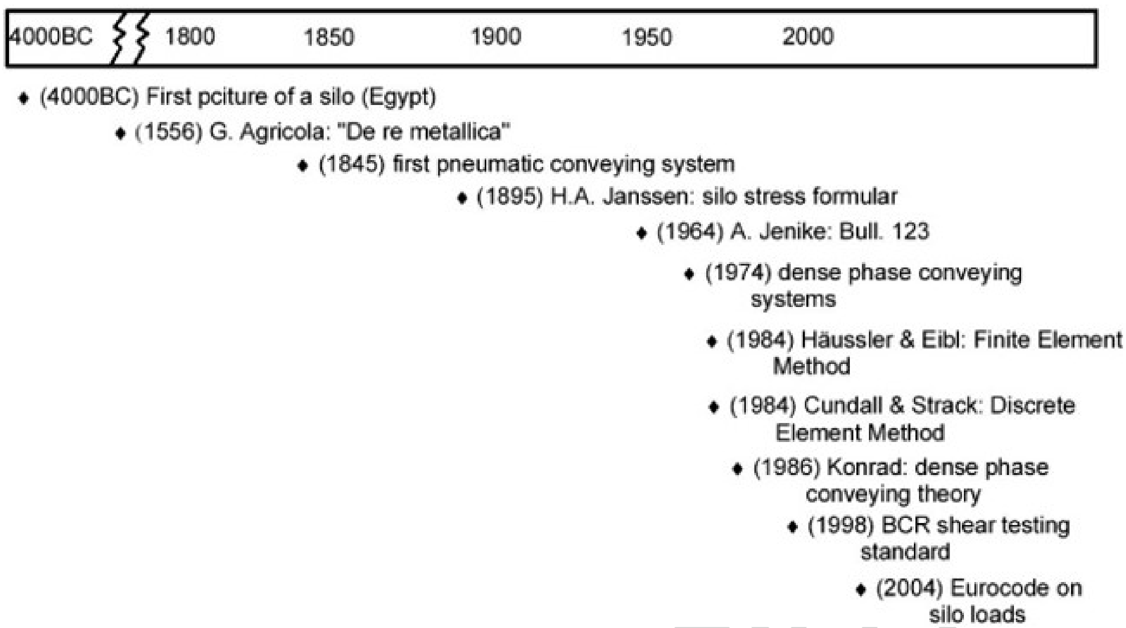



Figure 1: Time Ray of Bulk Solids Handling

Pneumatic Conveying is a comparatively recently developed technique for conveying bulk solids. The earliest known example of a type of pneumatic conveying system was used for collecting dust from a set of grindstones at a Peugeot plant in France in the middle of the 19th century. The first 'proper' pneumatic conveying system transported grain into silos in 1878. In 1898, a Prussian "Regierungsbaumeister" reported about pneumatic conveying of grains as a 'proven technology that holds great prospects'. By the mid 1920's, pneumatic conveying of grain was common. The first wave of scientific work on pneumatic conveying culminated in the 1950's when equations for the pressure drop in dilute phase conveying were developed (e.g. Barth, Segler). About a hundred years after its invention, the world of pneumatic conveying was revolutionized by the appearance of dense phase conveying. The first system called "dense phase" was marketed in 1974. About ten years later Konrad published his work on dense phase conveying and his model still compares well with the best twenty years later. The large interest in pneumatic conveying the developed during the 1970's and 1980's – spawned by such features as its flexible routing and ecological advantages – provided the incentive for a large amount of research on the subject in that period.

Obviously the many different aspects of bulk solids handling have assumed varying importance over the years. Figure 2 shows the approximate number of publications over the last 3 ½ decades in three different areas of bulk solids handling: silo technology, shear testing and pneumatic conveying. One can see that the total number of publications roughly follows the common exponential curve of publications, literature on shear testing has been fairly constantly written since 1980, while pneumatic conveying had its hay-days in the 1980's and is now almost constant on a lower level. Much of today's research work is focused on silo technology and here mainly on applying the ever-increasing computing power of the current numerical methods to the various aspects of bulk solids handling.

| | 1970 – 1979 | 1980 – 1989 | 1990 – 1999 | 2000 – 2009* |
|---|---|---|---|---|
| Silo-Technology | 2549 | 6113 | 7309 | 10327 |
| Shear Testing | 449 | 1236 | 1534 | 2248 |
| Pneumatic Conveying | 1125 | 1909 | 1279 | 1349 |
| Total** | 4123 | 9258 | 10122 | 13924 |

*) linear estimate from number for 2000 to 2003
**) References available in vtB-CEABA, COMPENDEX and Thomson Sci

Figure 2: Publications in Bulk Solids Technology

## 3. Characterization of Bulk Solids

### 3.1. Particle Properties

Any bulk solid is made up of two or more phases, the most prominent of which is the disperse solids phase: the particles. The other phases are the interstitial fluid (usually air) and any residual moisture adsorbed or concentrated in individual voids or capillaries. The particles are defined by their chemical composition, their size and shape. The two latter ones are in nearly 100 % of all bulk solids distributed parameters, since the size and shape of the particles in a bulk solid tends to vary.

It has to be stated firmly in any discussion of particle size for fine particles that for all but exactly spherical particles, there is no unique size parameter that sufficiently describes the particle. Instead, when describing fine particles by various characterization techniques, the method employed studies individual properties of a particle, such as volume, light scattering, and relates this to the same properties of a sphere. It is therefore important that the method used to describe the particle size distribution of a bulk solid measures a feature of the particle which is functionally important for the system studied. Such a parameter for pneumatic conveying purposes would be the terminal settling velocity of the particles.
Widely used methods for particle size characterization are laser light scattering measurements on the one hand and sieving on the other hand. When performing a sieve analysis, it is important to remember that American and International sieve series are not identical. Therefore giving particle size distributions in terms of sieve fraction vs. mesh is not unambiguous.

Since particle size distributions are almost invariably given as “diameter of an equivalent sphere”, it is necessary to characterize the actual shape of the particles as well. This is usually done by descriptive terms like “flaky”, “plate like”, “fibrous” etc. Figure 3 gives a standardized list of such shape descriptors from FEM 2.582.

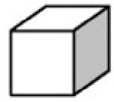
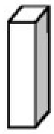
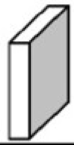
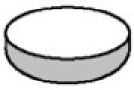
| symbol | designation | drawing |
|---|---|---|
| I | Sharp edges of approximately equal dimensions in the three geometrical directions.<br>Example: CUBE |  |
| II | Sharp edges, one of which is obviously longer than the two others in the other directions.<br>Example: OBLONG |  |
| III | Sharp edges, one of which is obviously shorter than the two others in the other directions.<br>Example: TILE, FLAT, ROD |  |
| IV | Rounded edges of approximately equal dimensions in the three geometrical directions.<br>Example: SPHERE |  |
| V | Rounded edges, one of which is obviously longer than the two others in the other directions.<br>Example: CYLINDER, BAR |  |
| VI | Rounded edges, one of which is obviously shorter than the two others in the other directions.<br>Example: WASHER, LENS, DISK |  |
| VII | Fibrous, stringy,<br>knotted, interlaced.<br>Example: FIBRE, THREAD |  |

Figure 3: Particle Shape Descriptors (courtesy of the Fédération Européenne de la Manutention)

To generate quantitative shape characteristics a multitude of aspect ratios are being used. Some aspect ratios are very straight forward (e.g. length vs. diameter of a fiber) but the definition of a unified aspect ratio for the general non-spherical particle is far from trivial.

One set of general dimensionless indices of shapes can be defined, if one constructs a rectangle around the profile such that its area is the smallest of all rectangles that could be drawn around the profile. If we assume that a and b are the sides of this smallest rectangle, A is the actual projected area of the inscribed profile and U is its actual perimeter, than the Hausner shape indices are:

elongation factor $\frac{a}{b}$

bulkiness $\frac{A}{a \cdot b}$

surface factor $\frac{U^2}{12.6 \cdot A}$

In recent years Mandelbrot's fractal dimensions have been introduced to describe texture and structure of fine particles. The basic idea is that the ruggedness of a particles surface, or the boundary of an area, can be described by adding a fractional number to the topological dimension. The topological dimension of a line being one and the topological dimension of a surface equals two. For a very rugged particle in three dimensional space, the fractal dimension of the particle surface would be two plus a high fractional number. Therefore fumed silica is known to have surface fractal of 2.9.

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**Biographical Sketch**

**Dr. Hermann J. Feise** has studied Mechanical Engineering at the University of Waterloo, Canada and the Technische Universität Braunschweig, Germany. After receiving a PhD from the Technische Universität Braunschweig in Process Engineering he came to work with DuPont as a principal researcher on solids handling. Today he is the senior research manager of BASF for Particle Formulation and Handling, covering the unit operations of drying, agglomeration, mixing and solids handling.

Dr. Feise is active in national and international professional bodies, such as the German GVC and the European Federation of Chemical Engineers. For both institutions he currently leads the working parties on solids handling and related areas. He is also a member of the "Kuratorium der Möller – Stiftung für Wissenschaft und Forschung", Hamburg and the scientific committees of many current, major international conferences in this field.

Dr. Feise has received various awards for his scientific work in the area of solids handling and has published more than 40 scientific papers.