5 Flow behavior of bulk solids

For moved bulk solids has one to distinguish between cohesive and non-cohesive behavior. A non-cohesive material like dry sand takes the form of a circular cone when it is being heaped on a horizontal level. Depending on the particle density and the internal friction arises always the same rise angle between the surface line of the cone and the horizontal level. The angle of repose is thus reproducible.

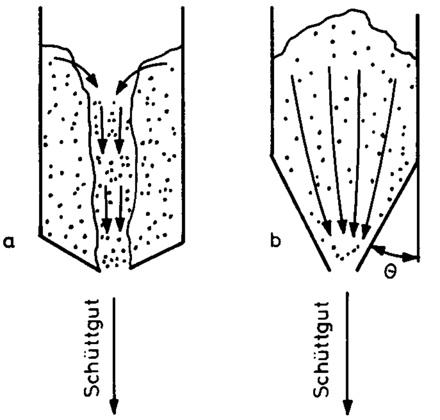

Fig. 5.1

During discharge of bulk materials from silos can occur funnel flow (a) and mass flow (b)

Cohesive material sets its deformation an additional resistance against. The size of this resistance is dependent of the compaction state of the material. For example expires moist compacted sand not from the form, even if it is standing on its head. Experience has shown, that the angle of repose of such materials is little reproducible.

The internal friction of non-cohesion bulk materials - only the flow behavior of such materials is the subject of all further considerations - is affecting all processes, in which relative movements in the bulk material occur. Quantitatively can this influence, for example be considered in the relationship for the discharge of bulk solids from silos.

5.1 Material flow in silos

Due to the gravity flows bulk solid by itself out of bunkers and silos and can be passed through pipes to their destination. The designing engineer has to do it with two issues. A silo must be constructed in a way, that the whole contained material runs evenly out. The outlet cross section must be large enough to prevent, that stable material bridges, which hinder the flow of the bulk material, occur.

For the given dimensions of the silo then arises also yet the question, how the per time unit outflowing material mass be influenced by the material properties. If the necessary geometrical conditions, for example, from lack of space can not be met, or if bulk materials with very different properties be stored in a bunker, a smooth and trouble-free operation is often only with the help of additional discharge aids guaranteed.

5.1.1 Silo design

Two different modes of flow can be observed if a bulk solid is discharged from a silo: mass flow and funnel flow (Fig. 5a). In case of mass flow, the whole contents of the silo are in motion at discharge. Mass flow is only possible, if the hopper walls are sufficiently steep and/or smooth, and the bulk solid is discharged across the whole outlet opening.

If a hopper wall is too flat or too rough, funnel flow will appear. In case of funnel flow (Fig. 5b), only that bulk solid is in motion first, which is placed in the area more or less above the outlet. The bulk solid adjacent to the hopper walls remains at rest and is called „dead" or „stagnant" zone.

Two steps are necessary for the design of mass flow silos for bulk material: The calculation of the required hopper slope which ensures mass flow, and the determination of the minimum outlet size to prevent arching. These parameters are measured in dependency on the consolidation stress with shear testers, e.g. with the Jenike shear tester or a ring shear tester.

The shear cell of the shear tester introduced by Jenike [5.1] consists of a closed ring at the bottom, a ring of the same diameter (so-called upper ring) lying above the bottom ring (Fig. 5.2), and a lid. The sample of bulk solid is poured into the shear cell. The lid is loaded centrally with a normal force N. In addition, a bracket is fixed to the lid. The upper part of the shear cell is displaced horizontally against the fixed bottom ring.

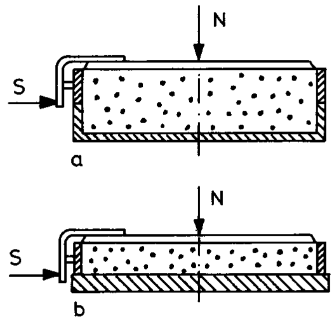

Fig. 5.2

Jenike shear tester for determining the friction inside the bulk solid (a) and between bulk solid and wall (b)

The hopper slope required for mass flow and the minimum outlet size to prevent arching can be calculated with the measured values using Jenike's theory [5.5].

5.1.2 Discharge rate

Equations for the discharge rate from a silo were established so far only empirically and almost exclusively for non-cohesive bulk materials. Mostly describe these equations only the respective trials with good accuracy.

In silos with symmetrical funnels is the mass flow of non-cohesive bulk material, whose effective friction angle corresponds to its angle of repose, being influenced by numerous parameters and dependencies [5.6].

$$\dot{M}_s \cong d_A^{2.5} \text{ to } d_A^{2.8}$$

$$\dot{M}_s \cong h^{0.5} \text{ to } h^{0}$$

$$\dot{M}_s \cong \rho_p$$

$$\dot{M}_s \cong d_p^{-0.18} \text{ to } d_p^{-1}$$

$$\dot{M}_s \cong g^{0.5}$$

d_A is the outlet diameter, h is the height of the filling, ρ_p is the particle density, d_p is the particle diameter, g is the acceleration due to gravity. In addition there is the influence of the opening angle θ in radian measure, that can be assumed as follows [5.7]:

$$\dot{M}_s \cong \theta^{-0.36}$$

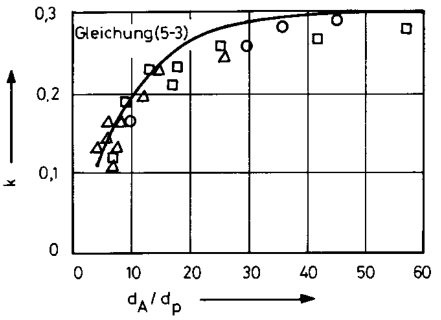

Fig 5.4

Evaluation of eq. (5-2) with the help of measured values for cohesionless solids [5.8 bis 5.10]

In addition there is the effects of the inner friction coefficient μ of the bulk material. μ is being equated to the tangens of the angle of repose ß:

$$\mu = \tan\beta \qquad (5\text{-}1)$$

The influence of the bed height h on the outflow can be neglected. The silo bottom pressure is changing itself only at very small filling heights, and the outflow becomes then non-stationary [5.6]. In an analysis of the measurements from three studies [8.5 to 10.5] could the very useful Eq. (5-2) for the calculation of the mass flow be developed [5.11].

$$\dot{M}_s = k\left(\frac{d_A}{d_p}\right)\cdot\frac{\rho_p \cdot g^{0.5} \cdot d_A^{2.5}}{\mu \cdot \theta^{0.36}} \qquad (5\text{-}2)$$

As the in Fig. 5.4 depicted evaluation resulted, exists between the proportionality factor k and the ratio of outlet diameter to particle diameter approximately an exponential relationship. The graph indicates also the limits: at values of d_A/d_p less than 5 to 10 is the outflow of bulk material no longer possible.

$$k\left(\frac{d_A}{d_p}\right) = 0.3\cdot\left(1 - e^{-0.1\cdot d_A/d_p}\right) \qquad (5\text{-}3)$$

The for the evaluation of the investigation results used data, were determined in experiments with glass, sand, lead, clay, resin and coal. The ranges of the individual parameters are stated in Table 5.1. The particle sizes of the investigated bulk solids range from 150 to 4000 microns.

With the help of the measurements by Taubman [5.12] could be proven, that Eq. (5-2) together with Eq. (5-3) also for much larger particle sizes can be applied. The results from experiments using gravel with particle sizes from 3 to 65 mm are reproduced in Fig. 5.5. The measurments for three outlet diameters show good agreement with the calculated values.

literature	sign	bulk sol.	d_p mm	d_A mm	θ grd	μ grd
[5.8]	○	sand glass sand	550 1100 2540	10 to 50	180	34 25 36
[5.9]	□	sand	160 to 910	6,6 to 11,9	60 to 180	35 to 42
5.10]	△	lead, clay, sand, glas, fertilizer, coal	790 to 4000	10 to 58	180	24 to 39

Table 5.1

Range of variation of the individual parameters in the investigations, evaluated in Fig. 5.4

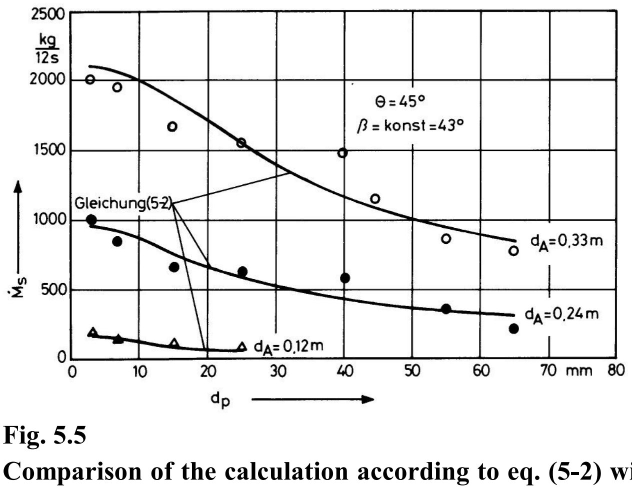

Fig. 5.5

Comparison of the calculation according to eq. (5-2) with the measured values on gravel [5.12]

In Eq. (5-2) is recognizable, that for the outflow of bulk materials from vessels (silos) especially the Froude number, formed using the outlet diameter d_A as characteristic length, plays a role:

$$Fr = \frac{u^2}{g \cdot d_A} = \frac{\dot{M}_s^2}{g \cdot \rho_p{}^2 \cdot d_A{}^5} \qquad (5\text{-}4)$$

5.1.3 Measures against outflow restrictions

During the storing of bulk materials in silos are being mainly discharge devices and discharge aids used as additional facilities. Discharge devices serve the dosing of outflowing bulk material and are thus at the same time discharge and feeding device. In contrast to that, discharge aids have the task to support the material flow from the silo against the occurring disabilities. Some discharge devices can also be used as discharge aids..

The flow of the bulk material is always then hindered, if the dimensions of the silo are not being attuned to the bulk material properties. Various reasons may be responsible. Either must the silo be installed without any knowledge of the properties of the material, or the silo could due to the spatial conditions not be designed according to the known material properties. Very different bulk materials are often being stored in one and the same silo. Then could in case of bad flow behavior of the material, discharge devices be needed, in order to protect the bin against bridge formation and blocking, and in order to change from a current funnel flow to the mass flow, if necessary.

The flow behavior of bulk material in the bunker can be changed fundamentally in two ways. One can influence the material properties, or uses constructive measures, to create a favourable flow profile of the material in the bunker.

A way to affect the properties of the bulk materials, is adding dispersants, also known as lubricants. Such lubricants are magnesium oxide, aerosil, urea, or diatomaceous earth with particle sizes down to 10-5 mm. The small particles distribute themselves among the actual particles of the bulk material and prevent in this way the cohesion effect.

Another way is the fluidization of the bulk solid by blowing air, in order to loosen the packed bed up. This measure is tantamount to the reducing the effective friction angle of the bulk material. To execute this, appropriate air distribution elements in the outlet section or at the outlet cone must be installed.

The measures described above, however, are often not suitable. On the one hand change the added dispersants the quality and composition of the bulk material, on the other hand can the loosened bulk material, for example, only poorly be bagged, because the bulk density be negatively affected through the additional air in the material.

Tapping with hammers and poking around with lances are for example measures, which the properties of the bulk materials not influencing, and at the same time the sliding of material on the wall of the outlet funnels ensure. Much more convenient and without great personnel effort can Vibrators be operated, which be installed outside the silo wall and be moved by a vibrator. Also can in silos inserted cushions be pulsatingly inflated by compressed air.

With the material and the surface quality of the outlet funnel can the wall friction angle between bulk solid and hopper wall, and thus the critical dimensions of the silo be influenced. Also with the help of plastic coatings of the walls can one achieve something.

While measures, taking effect on the wall, are only be useful, if mass flow occurs, can built-in discharge devices in the silo also be used in case of funnel flow. Also with bunker vibrators of different shapes and arrangement, which are being moved from outside, and with the help of agitators, can the flow of the bulk material be stimulated. By stationary devices and with a suitable shape of the hopper can the flow profile in the bunker be likewise favourably influenced. Discharge devices, which work at the same time as discharge aids, are for example flat floors with rotating arm or bottoms, which are elastically connected with an vibrating outlet.

5.2 Mechanical movement of bulk materials

In case of mechanically moved bulk materials, for example in screw conveyors, mixers and dryers, there are apart from the flow properties of the bulk materials additional parameters like the geometric conditions of devices and mechanical equipments as well as the manner of energy input. Therefore, it is in regard to the required drive powers and attainable mixing times or heat transfer coefficients, accordingly difficult to get information by calculations. Basic researches, in particular taking into account the aspects of scale-up, are only in insufficient extent available, so that for the planning appropriate documentation is missing. In practice is the plant engineer therefore dependent on the experiences of the respective device manufacturer.

The respective movement behavior of mechanically moving bulk materials becomes for example indirectly recognizable through the interpretation of heat transfer measurements during the heating of bulk materials in horizontal thin film dryers, which were published by Klocke [5.13].

5.2.1 Heat transfer in horizontal thin film dryers

Thin layer contact apparatuses with vertical heating surfaces have long been known for the vaporisation of solutions with low viscosity and for the rectification or distillation of fluid mixtures. Its rotating internals create mechanically a thin liquid film along the inner surface of a heated cylinder, and regenerate this film constantly. In this way high heat and material transfer can be achieved.

The thin film principle can also be used, for the cooling, heating and drying of pasty materials, powders and granules, as well as in order to perform reactions, where solids and liquids are involved. Fig. 5.6 shows the scheme of such apparatus, that is equipped with four blade rows, looking like paddles. The effective surfaces of the blade rows overlap themselves, and the residence time of the material can by the change of the angle of attack be adjusted. To increase the so-called hold-up, it has proven expedient, to arrange the heating surfaces horizontally. In addition, the design of the rotor was modified accordingly to the granulate form of the products, so that the material is distributed as evenly as possible along the wall in order to improve the heat exchange.

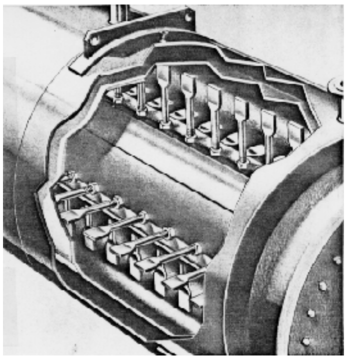

Fig 5.6
Horizontal thin film dryer with four blade rows (picture credits: BSH)

In Experiments in two facilities with diameters of 210 and 250 mm as well as heating surfaces of 1.2 and 1.5 m^2, five bulk materials were heated. In all experiments was the orientation of the blades identical: "transport in flow direction" in the entry zone, "transport against the flow direction" in the discharge zone and "neutral position" in the remaining area. Would be more "transport against the flow" chosen, so that the dwell time would increase, the wall coverage could be certainly improved, on the other hand would the drive power likewise grow considerably. Under consideration of the heat transfer on the one hand and the necessary drive power on the other hand, the largely neutral position of the blades has itself proven, as far as in case the use of drying gas not an additional conveying effect occurs.

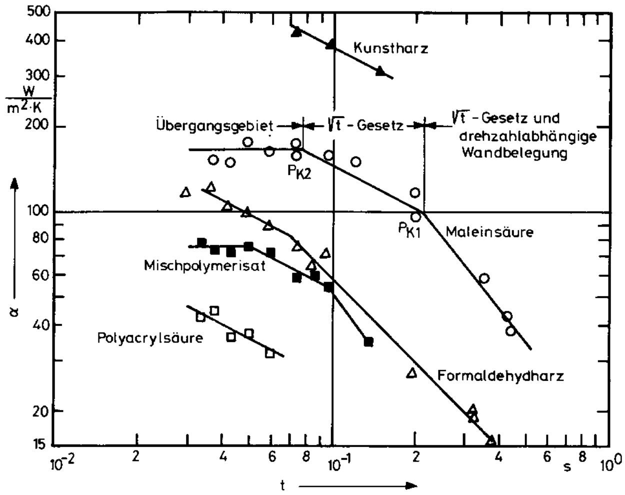

Fig. 5.7
Heat transfer coefficient α in dependency of the contact time *t* in a thin film dryer during heating of various bulk materials

Fig. 5.7 depicts the impact of the short-term contact during the heat transfer between the bulk material and the surface, as well as the variation of rotor speed. Represented is the size of the heat transfer coefficient α as function of the contact time t. The contact time is in thin film contact devices the time between two rearrangements at the wall. Its size depends on the rotor speed n and the number Z of blade rows:

$$t = \frac{60}{Z \cdot n} \qquad (5\text{-}5)$$

The relationship between the Froude number Fr, for which the diameter D of the device is used, and the contact time t looks like follow:

$$Fr = \frac{2 \cdot \pi}{\sqrt{g}} \cdot \frac{\sqrt{D/2}}{t \cdot Z} \qquad (5\text{-}6)$$

Due to the circulation of the product ring at the wall of the thin film device, is the actual contact time of the product greater than the value of t, which is being calculated by Eq. (5-5). This fact is here ignored.

The measurement results for the heat transfer coefficient, related on the whole heated area, which were determined at constant throughput and variable rotor speed, can be interpreted according to Fig 5.7 as follows. In the region of large contact times (low rotation speeds), grows the material coverage significantly with growing rotation speed, and the heat transfer rises steeply. After the operating point P_{K1} is reached, the increase of heat transfer corresponds to the

$\sqrt{t}$ - law for short-term contact; the material coverage remains seemingly constant.

The optimum operating point is being reached at P_{K2} because by the further increase of the rotation speed (shorter contact times) the heat transfer is no longer improved. Increasing frictional resistance of the bulk material on the wall or changed conditions for the force transmission between blades and bulk solid seem to prevent a further reduction of the contact time between the bulk solid and the wall.

Additional conclusions are possible, if one tries to summarize the measurement values with a single curve. Fig. 5.8 shows such a presentation, in which in addition to the heat transfer coefficient α and the modified contact time, the influence of the heat penetration coefficient $(\lambda c\rho)_{Sch}$, the mass flow rate $\dot{M}_s$ and the diameter d_p of the particles is becoming recognisable.

As Fig. 5.8 shows, grows the heat transfer coefficient with increasing bulk material throughput steeply - namely with $\sqrt{\dot{M}}$. Due to the larger quantity of bulk material is obviously also a larger material volume for the coverage of the apparatus wall present.

As expected, leads a greater heat penetration coefficient of the bulk material likewise to an increased heat transfer. The numeric value of 0.33 for the

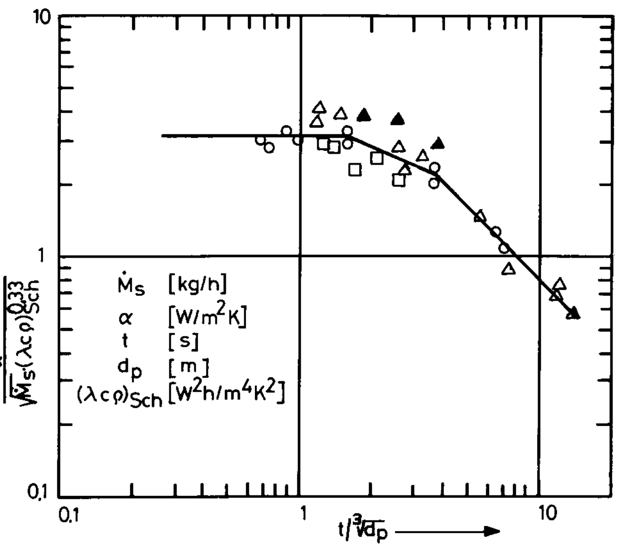

Fig. 5.8
Summarizing presentation of the heat transfer in thin film contact dryers

exponent, is already in other apparative constellations been determined.

The effect of the particle diameter that influences the contact time inversely proportional with the third root , corresponds to the behavior of bulk solids during the outflow from silos. There, smaller particle sizes causing larger material discharges.

Obviously, eases the larger number of particles per volume unit its relocation, and less resistance is being opposed to the shape change. In thin film contact apparatuses has this mechanism an opposite effect. In case of smaller particles, the frictional connection between the blades and the bulk solid is being deteriorated, so that higher rotor speeds are required, to achieve similar heat transfer rates.

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