A THEORY OF SUGAR DRYING

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by

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1. Executive Summary

This paper identifies the issues with the design of sugar drying systems in respect of sugar crystal size and regularity and to explain a theory of sugar drying. It sets out to define how drying occurs and what affects the drying process. The paper identifies some possible reasons for "caking" of sugar in storage conditions and steps that can be taken to avoid development of lumps in bagged sugar.

2. Introduction

This paper sets out a theory of sugar drying, based upon knowledge of the sugar drying equipment available in the industry and the practical commissioning and use of a variety of equipment types. Sugar cooling is a part of the drying process and is also discussed, as is the use of storage silos.

Sugar drying systems have been developed by a number of different companies and utilising different approaches to drying in terms of temperature, air flow direction and volumes, retention time, all based on an assumed crystal quality.

The equipment developed and commonly used includes:

Rotary Drum Dryer, with an air flow co-current with the sugar flow;

Rotary Drum Dryer and Cooler, with air flow counter-current with the sugar flow;

Rotary Drum Dryer / Cooler, with air flow co- and counter-current with sugar flow;

Fluidised Bed Dryer and Cooler, where air is cross-flow, at 90 degrees to sugar flow.

Other equipment including belt-type dryer, tray dryer and column cooler is occasionally used.

The theory of sugar drying is not affected by the equipment, but the air flow characteristics may be better in counter-current than in co-current units.

3. Understanding the Problem.

a. The Sugar Crystal. The sugar crystal is composed in units of 2 molecules, which crystallise in the monoclinic system forming hemimorphic crystals (Bartens Sugar Technology, 1998).

"Monoclinic" refers to a crystal with six faces and three axes of unequal length. Two axes are at right angles to each other and the third is inclined to the plane of the other two. A ream of paper with a long edge sloped at an angle is an example.

"Hemimorphic" is defined as: Having the two ends modified with unlike planes; -- said to be of a crystal.

The molecular structure is:

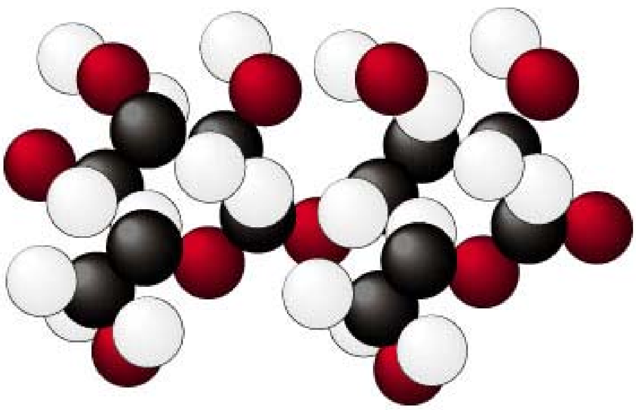

Fig. 1 Diagram of sugar molecule

The structure is an open one and permits the inclusion of other molecules, such as H_2O, within the crystal shape.

In practical manufacturing terms, the sugar molecules will often attach themselves to other solid particles and molecules as a base for development of the crystal and, thus, the sugar crystal will almost always include foreign matter within the crystal. This will normally have no impact on white sugar quality as the particulates are very small, but detailed analysis of a solution derived from the crystals will reveal other elements.

The sugar crystal actually looks like a rectangular block of crystal, a shape which all of us are very familiar. Figure 1 shows a single crystal, whilst figure 2 shows a group of crystals with variations in shape.

Fig. 1 Sugar crystal

Fig. 3 Magnified group of sugar crystals

b. Production of Sugar Crystals. There is no intention in this paper of going into the detail of the crystallisation process, which has already been dealt with in depth by many sugar technologists and chemists over the years.

Although the objective of crystallisation is to produce a pre-determined number of crystals of a pre-defined size, the reality is that the crystals produced in vacuum pans have a crystal size range, some narrower than others, a crystal regularity, a quantity of fine and coarse crystals, agglomerates and conglomerates.

A typical crystal distribution is an "Hysterisis" curve (shown in Red), centred on the target crystal size, known as the Mean Aperture (MA) and evenly distributed about that value. The narrower and taller the hysterisis curve, the lower the quantity of large and small crystals, known as the Coefficient of Variation (CV), present in the sample. The MA and CV are mathematically determined from a sieving analysis of the sample of sugar. The MA will be determined by the plant's customer requirements and may change for different products. The CV value is, in practical terms, the lowest number achievable in optimal crystallisation and will range from 28 to 32 for good crystallisation and up to 40 for poor crystal control.

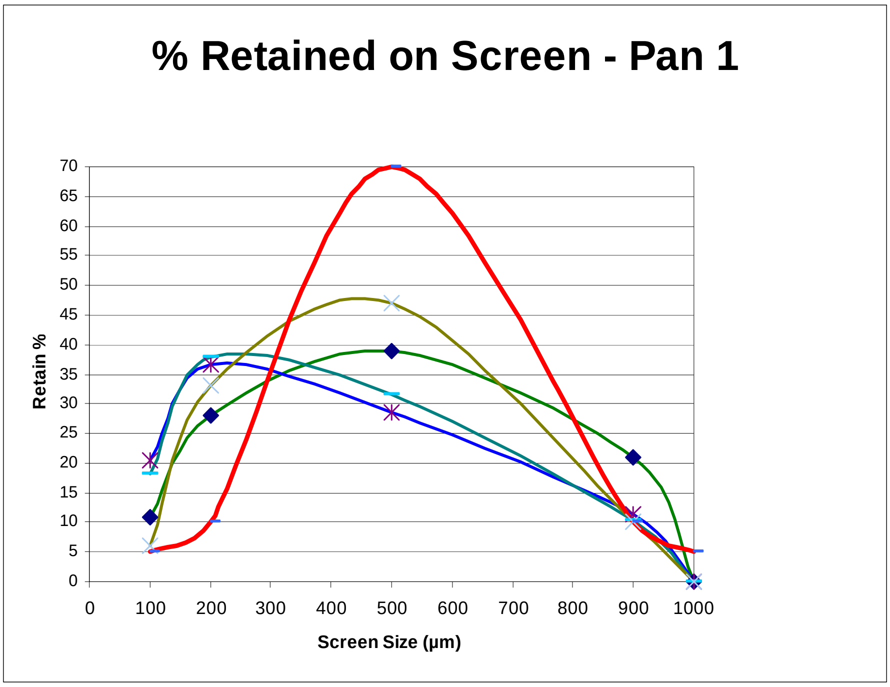

Fig. 4 Graph showing typical sugar screening results

This curve is notoriously difficult to produce accurately and repeatedly in sugar factories and refineries, so a range of examples of practical curves achieved in one factory are shown on the same chart, in four other colours. The one in dark yellow is a good one, whereas the ones in blue and brown are poor.

c. Impact on Sugar Drying Equipment. The designer and manufacturer of sugar drying equipment will base the design on an MA, CV and moisture content of the undried product sugar at a maximum throughput defined by the customer. Typically, these values will be 0.55 mm MA, CV of 28 and moisture of 1%. The net effect of the difficulty to produce the target MA and CV consistently is that the sugar dryer manufacturer is presented with a range of crystal sizes and shapes, from which he is expected to design a machine capable of removing the water from each and all the crystals.

d. Moisture in Sugar Crystals. Because of the open molecular structure, detailed above, of the sugar crystal, moisture, or H_2O molecules will be present in the crystal structure and can be divided into three types (Rodgers and Lewis, 1962-64), of which only two can be analytically measured:

- Surface water content; the water adhering to the surfaces of the sugar crystal and removed by evaporative drying. This can be measured using the Karl Fischer method with water-free ethanol as a dispersing agent.
- Included water content; not able to be measured because it is not possible to extract it from the crystal structure
- Total water content; by measuring this value, using the Karl Fischer method with a solvent, such as Formamide, as a solvent for the sugar, the inclusion sugar content can be determined by subtraction.

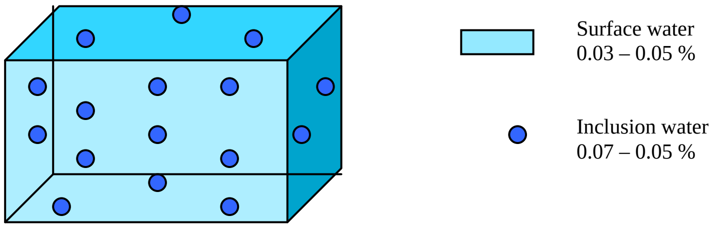

Fig. 5 Diagram of sugar crystal showing water locations

In freshly dried sugar, the Total water content should be < 0.1% with the Surface water content being 0.03 – 0.05%, leaving 0.07 – 0.05% of Inclusion water content.
The problem with the inclusion water content is that it is very difficult to extract, but will migrate slowly to the outer surface of the crystal over time in storage. The quantity of water involved in Inclusion water is a significant percentage of the Total water content of dried sugar and "caking", lumping together of sugar crystals can occur readily in storage, depending on the temperature relative to ambient and relative humidity in the storage facility.
Factories and refineries that install conditioning sugar silos and store sugar for at least 3 days after production will usually not have a problem with an increase in moisture content in their stored sugar, because the conditioning systems ill remove the moisture as it leaves the sugar crystal and the remaining drying of the sugar is continued in these systems.
Plants which bag sugar direct from production will tend to have a subsequent problem with increased moisture. The post-bagging storage conditions become more important, because:

a. the sugar will often be warm compared to the storage facility temperature at the time of bagging,
b. the bags will generally be stacked (either 50kg or 1 tonne) and the heat will be retained inside the stack for longer, so the outside bag will "cake" first,
c. the migrated Inclusion water has no way of being removed from contact with the sugar crystals and will gather into larger volumes, localising the "caking" effect.

The impact of moisture increase in bagged sugar also depends upon the type of packaging used. The graph below demonstrates the negative effect of using polythene rather than paper for the packaging material.

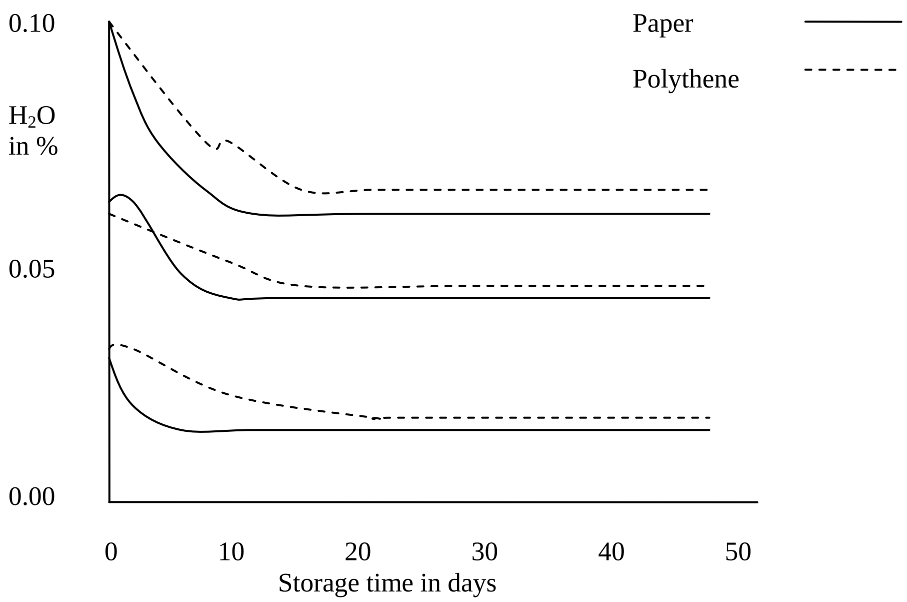

Fig. 6 Changes in water content of white sugar in different packaging materials (*Schiweck et al. 1978*), abstract from Beet Sugar Technology, Bartens, 2001

The use of poly-jute, poly-propylene and poly-paper bags, also desired by the industrial customers, actually has an adverse effect if used for unconditioned white sugar. For conditioned sugar, these packaging materials are suitable.

4. The Input Requirements

In order for effective drying and cooling of sugar to take place, the pre-conditions (upstream of the drying equipment) will need to be:

a. Good crystallisation of sugar liquor in the vacuum pans. The target should be for an appropriate Mean Aperture (MA), typically 0.55 mm and a good Coefficient of Variation (CV) of 28 – 30. This also means a minimum of conglomerated crystals, which will cause both colour and moisture retention problems.
b. Good centrifuging of the massecuite, including purging of the syrup and adequate washing to remove liquor from the surface of the crystal, but also sufficient spinning time to ensure that the surface water content is $< 1.0\%$.
c. Throughput conditions that do not exceed, for any part of any hour of operations, the design conditions for the sugar dryer.

d. Wet sugar conveying systems to the sugar dryer that minimise the crystal breakage, but also encourage natural water evaporation.

e. The wet sugar temperature at the sugar dryer inlet at an optimum temperature of 60 ^{o}C to permit evaporative drying to take place.

5. How Sugar Dries

a. Evaporation of surface water. The easiest and most obvious drying takes place from all the surfaces of the sugar crystal. The surface moisture is driven off, with the correct drying conditions around the crystal, leaving the permeable surface open for included moisture to migrate through. These "correct" conditions include:

i. An air supply around the crystal that is sub-saturated with water so that it can absorb water from the crystal surface. In counter-flow dryers, the air enters where there is the least free moisture on and around the crystals and the water content gradually increases as it moves through the dryer. If the air becomes saturated before leaving the sugar flow, maximum water extraction will not occur.

ii. An air temperature lower than the input temperature of the crystal from the centrifugals to encourage the water to lift off the crystal surface, from a higher to a lower temperature. Where the air temperature is higher than the input crystal temperature, there is a risk that the saturated layer of sugar liquor at the crystal surface will rapidly become super-saturated and seal the crystal surface, trapping internal water within the crystal.

iii. An air flow high enough to move the water away from the crystal surface, but not high enough to carry the crystal away. Fine crystals will be carried away with the air flow, both because they are light and because they will dry quickly, but this is a beneficial effect of removing the fines (dust) from the product sugar.

iv. An agitation system in the dryer, either by lifting and dropping or by stirring, vigorous enough to expose all surfaces of the crystal to the airstream, but not enough to cause excessive crystal breakage.

v. A mean sugar crystal size (MA) suitable for the design of the sugar dryer. Most of the sugar drying equipment has been designed for a defined throughput rate and a specific MA, in the range 0.5 – 0.7 mm, with an average of 0.6 mm. If the dryer is supplied with sugar at an average MA of 0.3 mm, then there will be approximately eight times ($=0.6^3/0.3^3$) as many crystals for the same bulk density and therefore throughput. The surface area of 0.3 mm MA crystals is a quarter of the surface area of a 0.6 mm MA crystal ($=0.3^2/0.6^2$). So, the net effect of halving the crystal size MA supplied to the dryer is a doubling (=8 * ¼) of the surface water content to be driven off and doubling the evaporation rate required of the dryer. The dryer will not be able to achieve this and the result will be that the inclusion water will be left in the crystal to come out at a later stage, often in storage, causing caking of the sugar.

vi. A retention time in the drying section, particularly, sufficient to allow enough time for the surface water to be driven off all the crystals. Most of the current equipment design is sufficient for this purpose.

b. Migration of inclusion water. This water is much more difficult to remove and requires two particular conditions:

i. A retention time in the drying unit to encourage it to move to the surface because it will move slowly and needs time to work its way to the surface. This retention time may be as much as 150% more than the retention time needed for the surface water, based on the relative percentages of water to be removed. None of the equipment currently designed takes this into account, mostly because of cost and space considerations.

ii. An air temperature lower than the crystal temperature to prevent sealing of the crystal surface, which would also prevent migration.

c. Evaporation of the migrated inclusion water. Once the included water has reached the surface of the crystal, the conditions for its removal are the same as for the surface water.

6. Cooling the Sugar.

The main purpose of the sugar cooling process is to reduce the temperature of the dried sugar to a level at which it can be safely stored and bagged. This temperature should always be less than 30 ^{o}C and between 20 and 25 ^{o}C whenever ambient conditions allow.

There is also drying advantage that can be gained when using some of the equipment currently available. Rotary and fluidised bed coolers will play a part in the driving off surface moisture and will also encourage the migration of inclusion water to the crystal surface, where it can be driven off.

In other types of cooler, such as column coolers, the opportunity to drive off moisture is reduced.

7. Use of Conditioning Silos

Factory sites with conditioning silos, or storage silos with conditioning systems, have a clear advantage over plants that have no operational storage, because silos provide the time (retention time) for the inclusion water to migrate to the crystal surface and to be driven off. Conditioning silos are a temporary storage system, generally no more than 3 days, whereas storage silos will often hold sugar for more than six months.

There are a variety of conditioning systems used in silos, but the three main ones are detailed as:

a. Under-silo air system. Widely used in the industry, this system supplies conditioned to the underside of the sugar silo, where it is blown gently upwards through the mass of sugar, allowing the air to percolate to the top, taking with it any free moisture. Above the sugar surface, the water-bearing air is removed at the top of the silo and recycled thought the air conditioner back to the silo bottom. Humidity control of the air above the sugar is limited.

b. Central air system. Some silo designs, particularly those with a central sugar inlet downtake, bring conditioned air into the sugar though the central downtake. The air has some percolation effect into the sugar, but most of the moisture removal occurs in the air space above the sugar. The water-bearing air is removed from the top of the silo and re-conditioned before being returned to the central downtake. The water removal depends upon the water rising through the sugar voluntarily and humidity control of the air above the sugar is limited.

c. Over-sugar air system. This system puts conditioned air above the sugar, generally at one side of the silo or from a ring distribution duct around the silo at the wall / roof junction and draws the water-bearing air from the top of the roof slope. The air does not percolate within the sugar and relies on the free water rising through the sugar voluntarily. Humidity control is achieved by adding water to the conditioned air stream in times of dangerously low humidity and not when humidity is high. Thus, accurate humidity control can be achieved.

Of the three systems, the under-silo air system is the most effective for the removal of migrated inclusion water after storage and the over-sugar air system is very effective for humidity control to minimise the risk of dust explosions.

8. Conclusions

a. The process of drying sugar is complex and requires careful analysis of the actual crystallisation conditions to achieve the desired result.
b. Crystal size (MA) and regularity (CV) are critical both in the design of sugar drying equipment and in their operation.
c. Removal of Inclusion water within the sugar crystal requires a longer retention time in the drying process than is generally economically possible in drying equipment.
d. Cooling of the dried sugar is necessary to achieve at least less than 30 ^{o}C and ideally lower than that.
e. The use of conditioning silos should always be considered, if possible.
f. If not possible, then the conditions in the bagged sugar storage facility become even more important.

References

Bartens Sugar Technology, 1998 has been taken as the main reference for technical content.

Experiential data and information has been drawn from work carried out for:

E D & F Man Sugar Ltd
SKIL
GEA Barr-Rosin Ltd