Sugar storage in silos: A slow conditioning approach

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Introduction

For decades bulk sugar conditioning and storage in silos has been one of the most widely discussed issues in the literature.[1,2,3] Large variation in types of silos, sugar quality, climatic conditions of sugar plants or storage facilities and other factors has allowed sugar technologists to accumulate significant experience in sugar storage and conditioning. It is well-known that product sugar emerging from dryers and granulators still contains enough bound moisture for it to be slowly released in storage. Failure to remove the excess moisture may cause the following problems in sugar storage and handling:

- Reduced flowability and caking, leading to non-uniform discharge and loading problems.
- Colour formation during storage.
- Crust formation on the walls reducing the effective volume of a silo.
- Bacteriological problems related to water condensation on silo walls.
- Safety-related problems when cleaning is performed.
- Silo cleaning becomes labour intensive and expensive, sometimes requiring specialised equipment.

All these problems are interrelated, with excess moisture being the common root. Thus moisture control in storage and transit of sugar remains the main issue of discussion between sugar technologists. Sugar conditioning is generally believed to be the best remedy for improving sugar flowability and quality.

Some facilities have one conditioning silo and several storage silos. Freshly produced sugar is loaded into a conditioning silo and a few days later transferred to one of the available storage silos. This approach certainly improves sugar quality but still has several drawbacks. Conditioning silos are usually designed for certain retention time, therefore fluctuations in product quality significantly affect the rate of water removal. Most conditioning silos are designed for retention time of 24-72 hours. Conditioned sugar reloaded into a storage facility is still subjected to moisture migration and possible hardening.

Simple experiments confirmed that even "matured" sugar has enough moisture to cause hardening problems. Dehumidified air was blown through a bed of sugar in a railroad car containing about 1900 cwt. of sugar, which had been previously stored in a silo for several months. Temperature and relative humidity (RH) of exiting air were recorded. After exiting air reached approximately 0% RH at 20°C the car was sealed and left for 24 hours. Measurements taken the following day showed RH in the head space of 65% at 20°C.

Though sugar conditioning systems work very efficiently in many sugar plants world-wide, installation of new systems or retrofitting of old silos is impaired by high capital investment.

Various sources[4,5] report that significant capital investment of US$2-4 million is required to convert existing storage silos to conditioning mode. Therefore, there is a need for an economical solution, which will combine benefits of sugar conditioning with the opportunity to retrofit most of the existing storage facilities. Increasing concerns over sugar quality and safety of sugar handling are driving forces in searching for new economical solutions for sugar storage and conditioning.

What would be considered an ideal conditioning system?

The requirements for ideal sugar conditioning and storage system may be summarised as follows:

- All produced sugar should be maintained at ideal storage conditions at 20-25°C and RH=55-60%.
- Excess moisture released by sugar crystals should be continuously removed. At the same time overdrying must be avoided.
- Air should be distributed evenly to avoid moisture migration within the bed of sugar.
- Sugar should be moved periodically to prevent intercrystalline bridging.
- Risk of dust explosion should be reduced.
- Temperature gradients leading to crust formation on silo walls should be reduced or eliminated.

Existing conditioning silos usually satisfy most of the criteria. Economic feasibility is still a rather weak point especially for retrofitting existing storage facilities.

Factors affecting storage and conditioning

Time of conditioning, air quality and quantity are not independent parameters and should be determined simultaneously based on the type of silo, amount of moisture to be removed and air distribution in the sugar bed. Retention time in conditioning silos is typically limited by production and shipment balance thus imposing certain requirements on a silo design.

Required air parameters are usually calculated as for a mass exchanger based on certain assumptions about heat and mass transfer in sugar. Calculations also vary depending on the project goal (new silo or retrofitting an old silo). This may be the reason for large variation in data available in the literature for specific air flowrates. A review by Mikuz and Budizek[3] lists a number of sugar conditioning silos in Europe with air flowrate varying 0.02

to 86 m^3/hr per metric ton of sugar. J. Bruijn *et al.*[12] indicate that the typical value accepted for many commercial installations fluctuates around 3 m^3/hr/ton. Calculations should be carried out on a case-by-case basis.

Understanding of the mechanism of mass transfer is extremely important to correctly calculate the air parameters required for conditioning. The drying process is driven by the difference between the partial water vapour pressure of a drying agent and the equilibrium vapour pressure corresponding to sugar moisture. Therefore, the commonly used assumption that the difference between RH of air and equilibrium relative humidity (ERH) of sugar is the driving force of a drying process is valid only when the temperatures of sugar and surrounding air are equal. However, this assumption is not valid for most practical problems.

The kinetics of moisture release by sugar may significantly affect the calculation of required air flowrates. The effects of conditioning temperature, grain size and other parameters on the conditioning process have been thoroughly studied.[12] Results indicated "that, in fact, very little air is required for conditioning." Reduction of air flowrate does affect the initial rate of water removal but has almost no effect after 48 hours. The authors also indicate that higher than required flowrates are generally applied just to maintain uniform air distribution across the silo. These are very important conclusions which helped justify our approach to sugar conditioning.

A typical drying curve is shown in Figure 1. The first "fast" period reflects the drying process when water is readily available for removal. Thus air parameters and flowrate will determine the rate of water removal. Most of the remaining surface moisture may be removed during this period. Various sources[3,7,12] indicate that conditioning air humidity and temperature have an effect on sugar moisture only during the first 24-48 hours. These numbers will vary depending on relative flowrates and parameters associated with the sugar and conditioning air.

In the second period, the rate of drying will be determined by crystallisation and internal diffusion through the amorphous layer of sucrose (an excellent review of the conditioning mechanism is given by D. M. Meadows[9]). At this time air ventilation may be helpful to stabilise sugar but excess air will lead to over drying. Air temperature, humidity or flowrate will have very little or no effect on moisture removal.

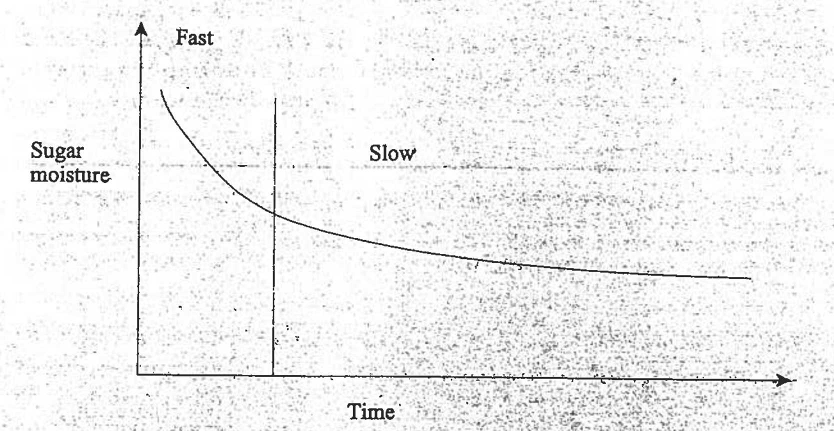

Figure 1. Typical Drying Curve

Today excellent commercial conditioning systems are available from various manufacturers. High cost is usually a payment for high quality. One should realise that significant number of silos in the USA and other countries were not originally designed for conditioning. Retrofitting is sometimes difficult or impossible to justify economically. The addition of double walls for heat compensation reduces useful volume of a silo and creates structural problems. Changing distributors, adding air circulation systems and redirecting the flow of sugar are complicated and expensive procedures.

It is worthwhile discussing how insulation or heat compensation of a conditioning silo affects the operating parameters. Heat compensation (or heating of silo walls) creates a uniform temperature profile across the silo. On the other hand because of the high cost this option, it may be only feasible for few installations. Our evaluations show that just the insulation of a relatively small 40 ft. diameter silo may cost several hundred thousand dollars. It is worth mentioning that the presence of insulation will change the temperature gradient across the silo wall but cannot be considered as an ultimate solution. Specialists from BC Sugar have indicated that in the absence of insulation, moisture migration to the walls cannot be eliminated but it will no longer cause problems provided the air parameters are correct.[6] This raises the question whether insulation of the silos is a necessary measure in retrofitting applications.

It is well recorded in the literature that good beet sugar quality can be maintained at temperatures about 20-25°C and relative humidity of the surrounding air at 55-60%.[13] These conditions correspond to dry mature sugar with an average moisture of 0.025%. It would be extremely difficult to maintain these conditions in the conditioning silos because of the fluctuations in product moisture and rates of water elimination. Maintaining the RH of air in the head space of a silo between 55-60% has a positive effect on agglomeration of dust particles and accumulation of static charge. Overdrying of the head space, which may occur when moisture is not readily released by sugar, leads to increased dust and a potential risk of explosion. Although some silos are equipped with misters for moisture control in the head space, few of them actually utilise this option.

The 'slow" conditioning approach

The goal of removing a significant amount of water during a limited period of time imposes certain requirements on a conditioning system design. Sugar conditioning is accomplished by supplying the drying air with a partial water pressure lower than that of air surrounding the sugar crystals. Typically, to provide sufficient water removal rate either a large air quantity is circulated or desiccants are used for air dehumidification. Significant air flows moving through a bed of sugar usually create a high pressure drop and cause excessive dust formation, therefore some degree of air dehumidification is usually required to provide sufficient drying capacity.

An alternative "slow" conditioning approach was introduced and analysed by a group of specialists from Amalgamated Research Inc. and Amalgamated Sugar Company for retrofitting an existing cluster of concrete silos. Typically one silo is loaded with freshly produced sugar, while the others are either resting or unloaded. The general approach was to condition all produced sugar and then maintain good storage conditions with continuous ventilation. Thus conditioning in the traditional meaning of the term will be applied to all stored sugar. The principle flow diagram of a system with one silo is shown in Figure 2. Air is circulated at a relatively low flowrate, and only a refrigeration unit was used for partial air dehumidification. No desiccants were required. Conditioning air has sufficient drying capacity to remove the excess moisture from sugar crystals and maintain sugar at optimal storage conditions.

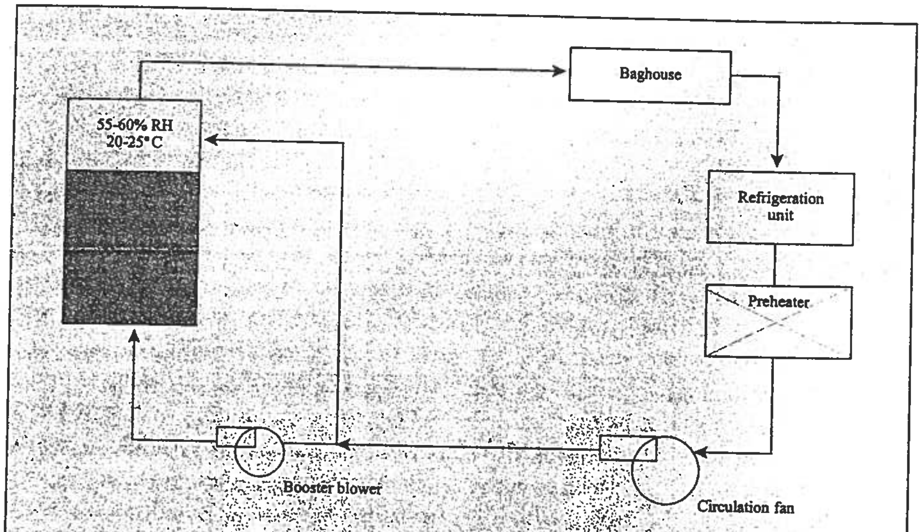

Figure 2. Principle Flow Diagram of a "Slow" Conditioning Silo

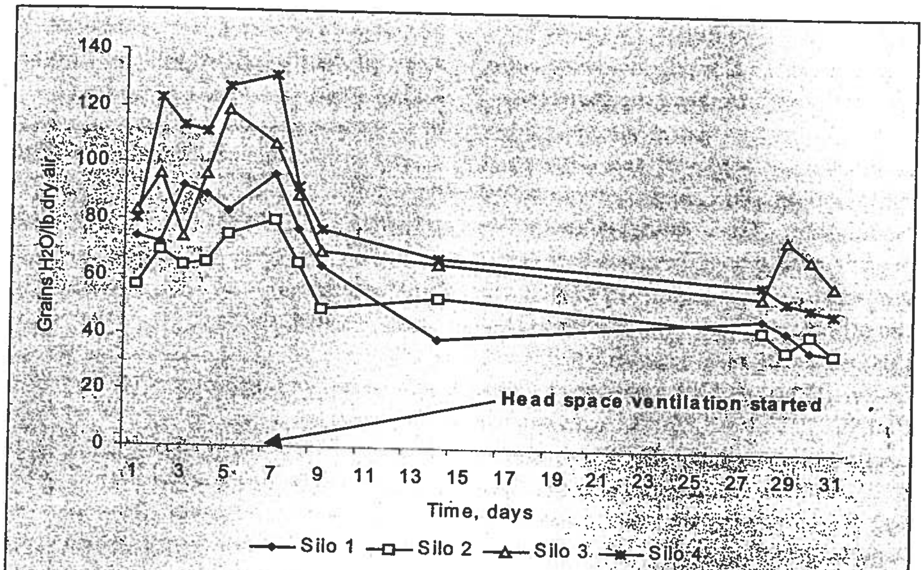

Figure 3. Effect of head space ventilation on absolute humidity

A portion of conditioned air is introduced to the head space of all silos maintaining constant relative humidity around 55%, thus minimising the risk of explosion. Several conditions have to be satisfied **simultaneously** for explosion to occur: minimum ignition energy, dust concentration within explosive range and ignition source.[8] By stabilising air RH in the head space of a silo at the safe level dust agglomeration and lower static charge can be achieved. The above author also reported that dust moisture content has a significant effect on the strength of explosion.

Continuous air circulation during the entire storage period ensures that water migration to the silo walls is limited to a narrow band adjacent to the wall and does not affect the bulk of the sugar. The system can be easily modified for a cluster of silos by adding a booster blower under each silo. One head space ventilation fan may be used for several silos.

The proposed system uses relatively low air flowrate (through sugar) of about 0.5 m^3/hr per metric ton of sugar. This quantity of drying air is sufficient to remove available moisture without overdrying the sugar. A fractal distributor manifold[10] was installed on the bottom of each silo preventing air from channelling inside the sugar bed and minimising the required pressure drop. Low air flowrates do not adversely affect air distribution across the silo. The main features of fractals – invariance to scaling and hydraulic equivalence of all outlets – has been proven in industrial chromatography columns used for molasses desugarisation.[11] Therefore, the booster blowers should only provide enough pressure to overcome friction within the bed of sugar.

Results and Discussion

A concept of "slow" sugar conditioning has been tested at the Nampa factory of The Amalgamated Sugar Company LLC. The project had been initiated mainly because of concerns about safety during silo cleaning. Complete unloading of the silos was difficult due to a high level of sugar build-up on the walls. It also created unsafe conditions for the cleaning crews. A cluster of twelve concrete non-insulated silos at

Nampa factory was partially retrofitted to accommodate the new concept. One 40 ft.-diameter silo was completely converted to the new operation.

A system for silo head space ventilation was installed as a first step towards the implementation of the new conditioning process. The absolute humidity in the head space (grains of water per pound of dry air) was monitored. It is clearly shown in Figure 3 that the air absolute humidity dropped significantly shortly after ventilation was started. However, the ventilation did not affect the moisture trapped within the bulk of the sugar.

The blower providing the air flow through sugar was installed in one out of twelve silos to test the new concept.

Figure 4 illustrates moisture removal from the conditioning silo during different operation phases. During this period the head space was still ventilated in all twelve silos. In addition to that, the conditioning silo had air flow through the sugar bed. As the silo was slowly filled with sugar, the RH in the head space increased. When the silo was filled completely the RH started decreasing gradually after less than one day of operation. This indicates that moisture was not readily available for removal. Conditioning air became completely equilibrated with the sugar only after 5-6 days. The moisture of sugar leaving the silo fluctuated around 0.02-0.025%.

Since the conditioning air was not completely dry, equilibrium was established within the sugar bed, which prevented sugar from being over-dried. The relative humidity in the head space did not dropped below 40%. Since the air is "averaged" between twelve silos, RH in the head space is expected to increase to about 55% when more silos are converted to the conditioning mode.

A portion of the instrument chart reproduced in Figure 5 reflects the changes in power consumption in the scroll motors. Typically, the curve fluctuations indicate the presence of lumps. The curve clearly shows the difference in sugar flowability, when the sugar stream was switched from a silo with head space ventilation only to a silo that was converted to slow conditioning method.

The pressure drop was monitored as a function of bed height in the silo. It was observed that the overall pressure drop through the distribution system and the bed of sugar did not exceed 3-4 psi when the silo was completely full. The low pressure drop can be explained by the relatively low air flowrate. It is also believed that the fractal distributor installed in the bottom of the silo contributes significantly to efficient operation. Because of hydraulic equivalence of all channels and independence of the distribution efficiency on fluid flowrate, air is distributed evenly across the column at low flowrates. This distinguishes the fractal distributors from conventional distribution systems based on pressure drop.

Most existing conditioning silos require additional insulation to avoid condensation on the internal surface of the silo walls. This was our main concern, when the experimental silo was retrofitted to test the new concept. In non-insulated silos a temperature gradient across the wall always exists. Since the dew point for the air surrounding well-conditioned sugar is around 10-13°C, wall thickness of

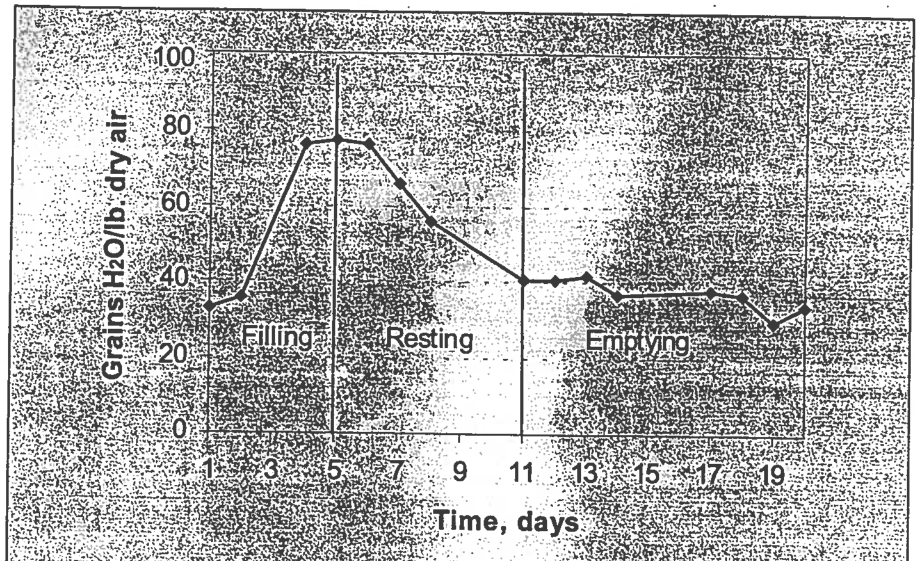

Figure 4: Moisture removal from the experimental conditioning silo

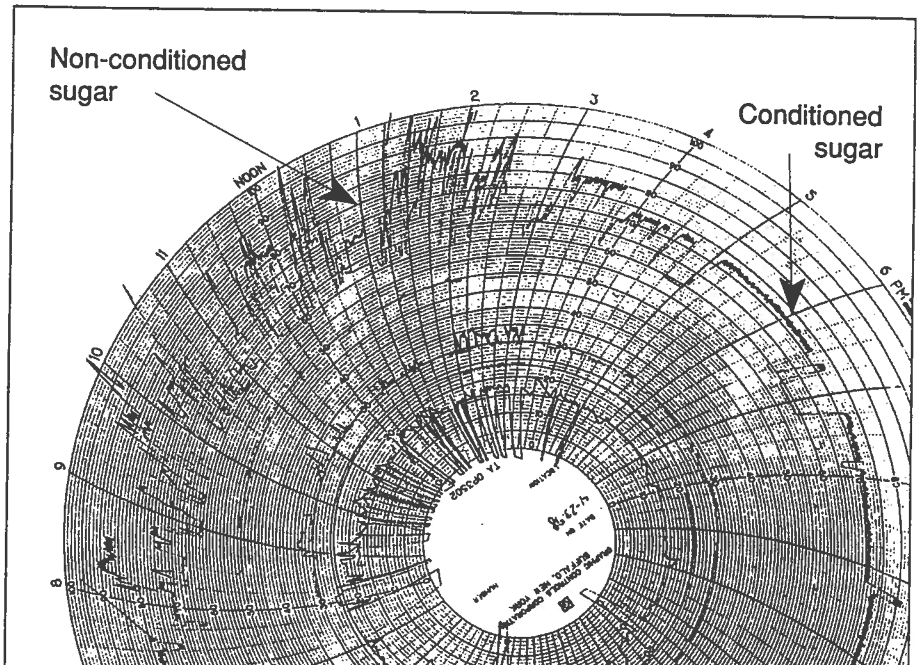

Figure 5. The instrument chart showing the current drawn by the scroll motor

Table 1: Conditioning Systems

Before	After
Relative humidity was high when silo was unloaded indicating that moisture was trapped within the bed of sugar.	No significant change in relative humidity.
Sugar was poked through unloading gates to initiate the flow with gates almost fully open.	Sugar starts flowing when the gates are slightly open.
Crust on the walls, sometimes coloured.	No new crust formation, old crust peeled off the walls.
Mounds of sugar up to 20 ft. high when silo is unloaded, unsafe cleaning conditions.	Sugar can be drained down to 4 ft. height which makes manual cleaning safe.
Condensation on silo walls.	No condensation.
Cleaning time – 770 man-hours.	Cleaning time – 24 man-hours.

about 10 cm does not provide sufficient insulation to prevent condensation on the wall. Therefore, the air adjacent to the silo wall should always reach a dew point without heat compensation. In the absence of air flow through the bulk of sugar the water would migrate towards the walls, eventually causing sugar hardening and crust formation.

During the winter months of 1998 the temperature in Nampa, ID fluctuated around -1 to 4°C during the day and –8 to -1°C at night. It is very interesting that no crust formation on the inside walls was observed. Moreover, the old coloured crust had been continuously peeling off the walls during loading-unloading cycles. The air circulation must have prevented moisture from moving in the radial direction. The water released by sugar crystals was readily picked up by the ascending air flow and subsequently eliminated from the recirculation loop. Evidently, maintaining a uniform air relative humidity inside the sugar bed is critical for reduction of sugar hardening and lump formation.

Observations before and after installation of the new conditioning system listed in Table 1 confirm that the test goals were successfully accomplished.

It is planned to convert two additional silos at Nampa factory to a "conditioning" mode.

Conclusions

A proposed "slow" conditioning method can be used efficiently for silos with relatively large storage volume when the conditioning capacity does not restrict the production schedule. The benefits of the new system are listed below.

- All produced sugar is conditioned, conditioning time is equal to storage time.
- It is economically feasible to retrofit existing storage facilities into conditioning units.
- Stable operation of conditioning system practically independent of fluctuations in product moisture, sugar grain size and CV.
- RH control in the head space reduces explosion risk.
- Crust formation on the walls is minimised improving safety in operation and cleaning.
- Optimal storage conditions guarantee high sugar quality and flowability.
- Final product moisture is no longer limited by the retention time in a conditioning silo.

It is noteworthy that the lack of silo insulation does not adversely affect the sugar quality. However the system has not been tested in extreme weather conditions.

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