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UNIT OPERATIONS IN THE SUGAR INDUSTRY 1/

by

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SUMMARY

The classical definition of a unit operation as a manufacturing procedure involving physical change in the material of concern is accepted and it is observed that every one of the usual unit operations may be encountered somewhere in the sugar industry or its by-product production.

There are also a few such as cane milling which have rather specifically been developed within the industry itself.

A range of important unit operations is briefly discussed with special reference to analytical and mathematical techniques and evaluation of behaviour and identification of optimum conditions.

The unqualified acceptance of the "bigger-and-better" syndrome is questioned with special reference to the development of sedimentation vessels.

Attention is drawn to fundamental differences between steam economy and rate of evaporation with respect to multiple effect evaporator calculations.

The paramount importance of crystallization as a unit operation is recognised.

The full value of power and steam generation in a sugar cane factory is yet to be recognised and developed beyond the boundary of the factory itself.

DEFINITIONS

A unit operation may be defined as a procedure in manufacture which involved a distinct, well defined and reasonably controlled pnysical change in the material of basic concern.

The unit operations of major concern in the sugar industry are those of:-

1. Raw material preparation
2. Extraction of juice
   (a) Milling
   (b) Diffusion
3. Screening of juice
4. Sedimentation
5. Filtration
6. Juice heating - Heat Transfer
7. Multiple effect evaporation
8. Single effect evaporation
9. Vapour condensation
10. Crystallisation
    (a) Associated with evaporation
    (b) Effected primarily by cooling
11. Centrifugal separation
    (a) Batch operation
    (b) Continuous operation
12. Crystal drying
    heating, cooling, ventilation
13. Transport of materials
    gas ⎤
    liquid ⎬ Fluid Flow
    two phase mixtures ⎦
    crystalline solids of various quality
14. Size separation of bagasse fibres
15. Combustion and steam generation, with associated
    (a) Boiler flue gas purification
    (b) Boiler ash handling
16. Electric power generation

17. Mass Transfer

This represents a quite formidable list which, without too much difficulty, could well be enlarged.

A number of text books have been published over the years dealing specifically with such topics as sugar factory machinery or as a manual or handbook specifically discussing sugar factory requirements.

On the other hand the fundamental chemical engineering approach of Unit Operations has developed as a basic discipline but its relevance to sugar factory situations is more usually of a marginal character.

The sugar industry can make (and has made) significant contributions towards the better understanding of such unit operations as evaporation and crystallisation with reference to an aqueous phase.

It has been well said that the sugar industry and closely related by-product developments employ in one way or another every one of the unit operations discussed in even the most comprehensive texts devoted specifically to the discipline.

The text book has not yet been written which would deal adequately with sugar manufacture from a truly unit operations approach. The industry still relies very largely rule-of-thumb capacity designing. Sugar technologists as such are seldom trained in the chemical engineering unit operations concepts. On the other hand, whilst chemical engineers should make very good sugar technologists, they are seldom employed in this way to their full capacity and seldom get the real feel of the operations as the technologist does. There has been recognisable improvement in this direction but the developments have been slow and frequently step-like in character.

It is not within the province of this paper to attempt a fundamental discussion of the unit operations listed which would be tantamount to writing the missing text book. Suffice it for the moment to identify the sections of sugar industry literature which are currently inadequately covered. Maybe this is an area for which some concern might be shown by an appropriate international organization. The preparation of a suitable comprehensive text is probably beyond the capacity of any single individual as normally situated and who has the appropriate expertise and experience in both fields.

Nevertheless some comment at least on some of the unit operations is pertinent.

A. Raw Material Preparation

Both sugar cane and sugar beet require careful preparation before the juice extraction procedure is undertaken. The technique selected is strongly dependent upon the nature of the raw material as well as on the character of the juice extraction procedure. In each case the sugar juice is contained within cells of the plant. In the sugar cane the cell walls must be ruptured to extract the juice, in the sugar beet the cell walls must not be ruptured but the sugar juice allowed simply to diffuse through the membrane. Sugar beets are treated invariably by a diffusion process. The term diffusion is applied to an optional procedure in cane juice extraction but in-correctly so. It is essentially a lixiviation process but it seems unlikely that terminology will be corrected at the present stage of the art. Many types of equipment have been patented and names registered which incorrectly includes the word diffuser.

Nevertheless it is of paramount importance to recognise this basic difference in mechanism.

Slicing the sugar beet and subjecting the product to diffusion has its own specialised problems and has yielded to basic mathematical treatment as a fundamental diffusion study. Today it is possible to extract something like 99% of the sugar in sugar beet on a continuous basis at high capacity - and such is being widely practised.

The sugar cane has been less yielding - the fundamental approach has either been more difficult or has had fewer highly trained scientists effectively engaged in its study.

We do know that both thermal and mechanical techniques can rupture the walls of the cell in the sugar cane. We are also better recognising that it is generally cheaper to expend energy on mechanical than thermal rupturing. Heat is still important in accelerating lixiviation.

Mechanical cane preparation techniques involve the use of knives and shredders. There are still many questions in this area to which the answers are multiple or inadequate.

1. What kind of knives should be used?
2. How should they be used in a specific set?
3. How many sets of knives should be used?
4. How best can we optimise the expenditure of energy by knife installations?
5. What kind of shredder should be used?
6. How should the shredder be used in association with the knives and/or a crusher unit?
7. How best can we optimise over-all energy input?
8. What is the energy input at the preparation stage in relation to the energy required for milling?
9. Should we use two shredders in series?

Other important relevant questions readily spring to the minds of those who have been directly concerned with the installation and operation of cane preparation units.

However the most important and probably most basic question which we can ask in this context still remains very largely unanswered, and too often is not even asked.

Question: How do we measure the effectiveness of any cane preparation device?

Probably the best answer which we have so far is some means of measuring the juice in open cells as distinct from juice in closed cells. It is assumed (probably correctly) that the juice from the open cells can be extracted by cold water lixiviation whereas boiling water lixiviation extracts the whole of the juice. The latter assumption is possible correct, but we still need to know more about the mechanism of cell rupture. Some real information on this subject is now being obtained by the application of electron micrograph techniques at suitable (generally moderate) magnifications.

Unfortunately techniques designed to obtain the above information are time-consuming, it is often too long to wait for the answer and only a limited number of samples can be studied in reasonable time.

One of the more successful pragmatic approaches has been simply to measure the bulk density of the comminuted fibrousproduct under standard conditions of pressure. A crude relationship between the observed value and correctly measured data can serve as a useful first approximation guide and the bulk density measurement has the advantage of being simple, speedily accomplished and readily understood.

B. Milling or Diffusion in the Sugar Cane Factory?

This is probably one of the most perplexing questions which can be phrased in the context of present day practice in a sugar cane factory. Unfortunately many of the installations of diffusers have been in situations where milling practice has been of a low standard and those well skilled in the art of milling contend that equally as good results could have been obtained if equivalent attention had been given simply to improve the standard of milling by well known and tested techniques.

Two important disadvantages of diffusion which are now surfacing as the result of more large scale factory experience are the inflexibility of most diffusers with respect to rate of cane supply and the cost of maintenance is proving to be higher than had been anticipated.

There is one obvious factor in the discussion and that is - in a sugar cane factory it is not possible to displace all of the mills by a diffuser. It is still necessary to have at least two conventional type mills - one before and one after the diffuser - and often desirable to have three or even four.

The method of extraction measurement leaves much to be desired in either case, but especially so in the case of the diffuser. To date we really only are able to measure sugar in product juice and residual bagasse. We have no reliable means of measuring sugar lost by hydrolysis in the process and diffusers are well recognised to be much more prone to such losses.

C. Operating a Conventional Sugar Mill

The conventional sugar mill is a 3 roll unit developed first approximately 100 years ago and until recently shown little change. Units of this mill are installed in series and may or may not be preceded by a two or three roll crusher. The basic question remains unanswered - when does a three roll crusher become a first mill?

Having recognised the factors which are important for improving the effectiveness of the conventional mill it soon became evident that implementation of any of the necessary improvements resulted in a fall-off in the capacity and subsequently the effectiveness itself, of the milling unit.

The cells need to be ruptured - finer preparation does this. The finer the preparation the more difficult it is to make a mill accept the feed. Better lixiviation needs more water and a higher temperature - each of which likewise makes it more difficult for the mill to accept the feed.

Much attention has been given to increasing the roughness of roller surfaces by arcing and spot welding, multifarious feeding devices have appeared. The three roller mill fitted with a heavy duty pair of pressure feeding rolls has almost become effectively a five roller mill.

Much has been done to transform the "art" of mill roller setting to a "science". There still remains the factor which can only be empirically determined in situ called by engineers in Java in the 1920's - the squirting factor but perhaps better known today as the re-absorption factor.

Where do we go from here?

The author personally prefers just to do a complete materials balance of fibre, water and "brix" for all stages of the milling train including the feed condition of the mills - a fundamental chemical engineering unit operation analysis. Seldom attempted by others but usually revealing of local weaknesses in the author's experience.

It is well recognised that a mill has difficulty in accepting a wet feed. The moisture content of bagasse leaving a mill is always performed for the last mill in the train, often also for the first and occasionally for intermediate mills. Attempts to effectively sample and analyse bagasse fed to a mill have almost invariably been unsatisfactory in the experience of many. Possibly the only satisfactory way to obtain this figure is to calculate a materials balance - a simple, straightforward easily computerized arithmetric operation.

The author has had some success in further taking advantage of this information to rearrange imbibition systems to obtain better feeding qualities - and hence capacity - without loss of extraction and furthermore to allow precipitation to be pushed to its logical conclusion in terms of fineness.

The multiplicity of variables and their recognised inter-relationships of complex predictability have provided the opportunities for never ending discussion and controversy in the areas of milling practice. Patient research has provided much useful basic data on such items as friction coefficients in feeding, angles for feed chutes, placement of feed rollers, groove characteristics and other items relevant to mill feeding behaviour. The author is firmly of the opinion that it will only be by taking the next step of regular and reliable analyses of materials balances that further significant developemnt in milling can be expected.

Diffusion or lixiviation in the cane industry is still very largely in the trial-and-error stage of development. A variety of devices have been the subject of experiment in small scale and large scale situations all aiming to extract more juice from the cane. Some data of a more fundamental chemical engineering character are beginning to appear. As for milling and for sugar beet diffusion it can be anticipated that it will be this approach which will in the long term be the most productive of real development.

Question: In what way can we mathematically inter-relate the two factors of capacity and extraction to give the best objective rating of the operation of diffusion or milling/lixiviation units?

D. Screening

An elementary unit operation applied to juices for the separation of fibre, to bagasse for removal of fine fibre for use as a filter aid or separation of pith in depithing techniques, to sugar for market oriented sizing, but how often is a unit operations analysis made of the effectiveness of a screening operation? We just do not have any such data, the very idea is almost unheard of. The screening operation is never thought of as a major unit in the flow sheet - and yet how important an effective screening operation really is?

There may not be much direct noticeable gain in terms of dollars and cents but a smoother flow of materials is always a worth-while achievement.

There is an abundance of data on screen capacities especially by manufacturers but effectiveness in situ is something which must be measured.

Questions:

1. What type of screen is suitable for a particular application?
2. How effective will this be at various capacity ratings?
3. Why do we need a screen for the application?
   Is there an alternative and more suitable technique?
   (e.g. use of chokeless pumps instead of juice screens)

E. Sedimentation

History has seen this unit operation change from batch type of operation to single tray continuous units followed by multi-tray units of progressively increasing dimensions. And then disappointment began to be become recognised in the "bigger-and-better" syndrome. The multi-tray units persisted in giving little better performance (if any) than a single tray unit of comparable cross-sectional area. Empirical attempts to discover corrective measures resulted chiefly in defining acceptable terms for reference of behaviour characteristics. It was not until systematic studies were made of circulation patterns and of sedimentation characteristics of the flocculent precipitate that effective corrective measures began to appear. Now there are several manufacturers of appropriately improved equipment.

The analytical techniques which finally proved to be successful needed little that had not been known in the science twenty years earlier.

F. Filtration

Capacity ratings in filtration operations are of substantial concern to all sugar manufacturers but little has been done by way of systematic studies of such parameters as porosity and permeability of cakes, the influences of particle size and shape, filter aid characteristics and evaluation in fundamental terms. This type of information is needed with appropriate basic study if any significant advance is to be made in this area.

G. Heat Transfer

Sugar processing involves the transfer of substantial amounts of heat for which the following applications are clearly defined:-

1. Juice flow inside tubes (vertical or horizontal)
2. Steam or vapour condensation around juice heater tubes
3. Multiple effect evaporators
4. Single effect evaporators
5. Drying of sugar - also involving mass transfer
6. Furnace gasses and steam generation
7. Air heater and/or economizer attachments to the steam generator

To a large extend straight capacity data from existing types of equipment are used to design new units. Fundamental treatments are possible in conformity with basic techniques well established for units of the type used in the sugar industry. Factors of special concern, although by no means unique to the industry, include such as the type and nature of the scale in juice heaters and evaporators, non-condensible gases in steam and oil in exhaust steam from reciprocating engineers. The combustion of bagasse from sugar cane represents heat liberation from a somewhat specialised type of fuel. Little is known of film transfer coefficients in massecuits and design depends entirely on general capacity information.

H. Multiple Effect Evaporation

In the sugar industry these units represent a substantial capital investment and are probably used more extensively than in any other single industry. A great deal of attention has been given to the steam economy involved and a high degree of sophistication has been achieved from this point of view. On the other hand basic knowledge of heat transfer characteristics are much less clearly defined. Recent types of long tube evaporators have been introduced to the industry and these have represented a worth-while development in heat transfer characteristics.

It is worth recording that, at least in many developing countries, the evaporator capacities are significantly inadequate with respect to units before and after. The net affect which has been observed has been to deliver low concentration syrup to the pan stage. This reduces the capacity of the pan stage by requiring more evaporation and depreciates the steam economy by requiring this evaporation to be at single rather than multiple effect. Too often the ailment has been ill-diagnosed and additional pan capacity has been recommended rather than additional evaporator capacity.

Another common failing has been an inability to recognise the difference in effects of operation when requiring an increase in evaporative capacity rather than in steam economy (or occasionally vice-versa). Changes which improve steam economy seldom result in increased capacity even though there may be an over-all increase in heating surface. Increase in heating surface can be arranged to increase capacity, but the two different effects are not infrequently confused.

As with other unit operations it is only by calculating a complete heat and mass balance and calculating individual heat transfer coefficients for each vessel is it possible to get a real understanding of just what is happening. The use of over-all capacity data for design purposes can, and frequently does, give incorrect answers when examining proposals for expansion programs.

Question: Are we quite clear on the differences between factors influencing evaporation capacity and factors influencing steam economy?

I. Single Effect Evaporation

This normally refers to the operation of vacuum pans. In these we are seldom concerned about steam economy - little can be done to change this. On the other hand we are seriously concerned about capacity but knowledge is inadequate on such factors as heat transfer coefficients - both over-all and film coefficients, circulation patterns within vacuum pans and the factors which influence and control circulation.

We seem to depend very heavily on the generation of circulation by vapour bubbles during boiling. Recent studies of the circulating power of such bubbles reveals them as being very inadequate indeed, for they coalesce very soon after formation and as they coalesce they loose most of their ability to generate circulation.

J. Crystallization

This unit operation is the climax of procedures employed in the production of sugar. Here we see for the first time the final product beginning to appear in recognisable form. It is essentially a mass transfer problem between a liquid and solid phase simultaneously operating with rather complex heat transfer problems. From the point of view of the sugar factory manager and his operating staff attention must be concentrated on productivity in rather superficial terms, the only terms which can reasonably be understood in relation to the important aspects of relating production to cost factors.

Successive stages of crystallisation are invariably practised. It is unusual to take time to ask the question why this should be and are there any alternatives.

The purity of syrups, massecuites, molasses and sugar are the units used for control purposes. But the units are often far from correct and at times misleading. The units are those of apparent purity depending upon the relatively simple measurement of polarisation and brix. They have the advantage of simplicity and have been sufficiently reproductive to enable them to be universally accepted for this purpose.

On the other hand if we try to use them for material balances we get into all kinds of difficulties because of the errors inherent in the system. The system, in practice generally yields moderately good results but when an improvement in results is attempted the limitations of the system become very significant.

The commonly considered alternative of performing sucrose and total solids analyses are occasionally resorted to for limited periods but with limited success. The analytical difficulties are significant and the desired precision not easily attained especially if experience is inadequate.

The author has obtained satisfaction from accepting a log-log relationship between true purity and apparent purity and interpolating values from the true purity of final molasses samples taken to represent the end product of the material being processed. Adequate time and precision of technique may be expended on achieving a correct analysis of the final molasses sample.

Mathematically the following relationships are then used:

$$\frac{\log\left(\frac{\text{True Purity}}{100}\right)}{\log\left(\frac{\text{App. Purity}}{100}\right)} = C$$

$$\text{True Purity} = \left(\frac{\text{Apparent Purity}}{100}\right)^{c} \times 100$$

The author is well aware of the inaccuracies which can be associated with such a technique, but in his experience the advantages have substantially outweighed the disadvantages providing a basis for materials balance calculations which at least give rational results from which real deductions can be made.

Much fundamental data such as sucrose solubility in pure and impure solutions, viscosities of saturated solutions, viscosities of massecuites and so on have been slowly accumulating especially during the past 20 years which have been of material assistance to further rational explanations of sugar boiling behaviour.

There are in fact three major groups of factors of concern which must be taken into account when planning the crystallising programme. These may be simply described as:-

1. The boiling route
2. The equipment employed - mainly referring to the boiling pans
3. The instrumental control criteria and their application

By boiling route is meant the flow sheet which is adopted to implement the required stages of crystallisation to obtain the best recovery of sucrose in crystal form.

The pans are of concern from the point of view of capacity, rate of heat transfer, circulation pattern and various specific design features.

Instrumental methods of control may vary from simple temperature and vacuum measurement to recordings of complex physical criteria for complete automation.

It has long been recognised that even the most sophisticated automatic control procedures can do little to improve poorly designed or inadequate pan boiling equipment.

It is seldom so clearly recognised how important it is to employ the most suitable flow sheet for the circumstances.

Questions:

1. What are the significant criteria of concern when planning the sugar boiling procedures?
2. How do we best employ these criteria, especially when faced with conflicting behaviour patterns?

K. Crystallization by Cooling

This stage of crystallisation is performed in batch or continuously operating vessels. Some of these may be equipped with water cooled surfaces, others depend only on air cooling.

The procedure is almost, but not exclusively, confined to the last massecuite in the boiling cycle. Both rate of crystallisation and rate of heat transfer are important. Massecuites must not be chilled too suddenly, crystal size and crystal content require attention as also the purity drop in the operation. It is the last opportunity to extract crystallizable sucrose from the mother liquors and when handling large quantities of material small differences in exhaustion can have a significant influence on financial returns.

L. Centrifugal Separation

The only technique which is used commercially for the separation of sucrose crystals from mother liquor is the basket type centrifuge. These are largely of batch operation but a progressively increasing proportion of installations are of a continuous type especially for final stage separations.

Development has been in size, power, power transmission techniques, automatic time cycling control and finally continuous operation.

In all circumstances three or sometimes four stages are recognisable (1) separation of cyrstals (2) washing with water and (3) drying with frequently the additional procedure of steaming introduced at various stages.

It is pertinent to ask just what is happening at each of these stages when planning the details of the separation cycle.

The viscosity of molasses saturated at different temperatures, the porosity and permeability of the bed of crystals, the size of crystals and the washing and drainage behaviour are important properties of the materials whereas diameter and depth of basket, rate of rotation, acceleration and braking times are some of the machinery characteristics pertinent to their design and use.

M. Crystal Drying

This is a problem in combined heat and mass transfer involving the surface layer of syrup. For keeping qualities the equilibrium humidity moisture values are of concern. These have been resolved in various relationships such as the Dilution Indicator or Safety Factor in terms of which the keeping quality, especially of raw sugar, is evaluated. The heat of attachment of water to the surface of the crystal has been evaluated and thermal conductivity of the crystal itself is important for cooling the crystal to minimise thermal development of colour during storage.

N. Steam Generation

The steam generator has its own special terms of evaluation involving problems in heat transfer and fluid flow. The sugar technologist seldom specialises in this area of concern leaving it largely in the hands of equipment manufacturers and suppliers and/or consultants. This can lead to unfortunate situations where optimisation is not necessarily achieved. Large operators are usually less affected than smaller ones as they can employ more staff with a wide enough range of specialization to cover effectively all aspects of steam generation with whatever fuel may be involved.

O. Electric Power Generation and Reticulation

This also is a highly specialised area for concern usually unlikely in a high degree of dependence on outside advisers except in the case of large operators. An important item in electric power reticulation in a sugar factory which requires specialised attention is the power factor which can be substantially depreciated by the development of large capacity batch type electric centrifugals.

P. Water Cooling

A substantial proportion of sugar factories find it necessary to recycle condenser water which involves a cooling system such as a spray pond or tower. The unit operation involves complex heat and mass transfer problem in psychiometry.

Questions: The following questions are pertinent for discussion for each unit operation in the sugar industry:

1. What function does this particular unit operation really perform?
2. How should it be operated for fullest advantage?
3. Are there alternative means of performing the operation?
4. Is the operation really necessary and if so why?

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