PREPEX – A HAMMERLESS SHREDDING TECHNOLOGY

LOUBSER R C, SMITH G T AND DAVIS S B

Sugar Milling Research Institute, c/o University of KwaZulu-Natal, Durban, 4041, South Africa
rloubser@smri.org

Abstract

The Sugar Milling Research Institute (SMRI) has investigated an innovation which could take the sugarcane processing industry into the future: cane preparation without knives and shredders. The technology is a complete break from the past, with knives and shredders being replaced by water, bringing advantages centred on reductions in maintenance and downtime, as there will be no more wearing faces.

Outside of the sugar industry, the use of very high and ultra high pressure water for cutting and surface preparation has increased rapidly in recent years. A demonstration of the use of water jets for preparation of surfaces for rust prevention coatings stimulated the idea of shredding sugarcane using water jets. Trials at the SMRI showed that the technology can be used successfully for shredding sugarcane. International patents for the process have now been lodged.

This paper details the trials conducted as well as some of the challenges faced as a result of this new area of research. The parameters pressure, flow rate and power, formed the basis of many discussions, and the terms 'nozzle attack tip' and 'stand-off distance' became new buzz phrases at the Institute.

One of the major challenges is to determine ways to minimise overall energy consumption, such as reducing evaporator loading by using juice instead of clean water for shredding. This has proven to be a substantial hurdle since manufacturers of very high pressure pumps are unwilling to certify their pumps for this fluid and conventional high pressure pumps cannot provide the pressure required for this process.

Keywords: shredder, high pressure jet, costs, extraction, nozzle assembly, wear

Introduction

The weekly or fortnightly stop day has become part of the sugar factory ritual, as the cane preparation equipment must be refurbished at regular intervals so that it can function effectively. The result is that mill capacity or season length are adversely affected.

It is clear that there are strong drivers to eliminate or at least significantly reduce the time taken and costs involved in maintaining the preparation equipment, and the costs of wear of the preparation equipment has formed part of many studies. Reid (1996) related the cost of soil in cane to the cost of preparation equipment refurbishment, while other cost studies were done by Moult (1980 a,b), Koen (1980), Gómez *et al.* (2005) and Gómez *et al.* (2007), which illustrate the interest in understanding the cost of preparation.

There have been many attempts to find the ideal material for knives and shredder hammers. Examples of these were reported by Gómez *et al.* (2008) who investigated several materials including tungsten carbide and ceramics, as did Mason (1977) and Schlaudraff (1983). The outcomes of these studies have been incremental improvements and no substantial breakthroughs have been reported. The most likely solution is to move away from the conventional hammer mill approach and seek an alternative method of preparing cane. An alternative approach using ball milling was suggested by Edwards and Rogash (1987), but they concluded that it was unlikely to replace the conventional equipment.

Innovation is mostly either a novel application or an improvement of what is already known. One technology which has found ever-increasing applications in many industries is high pressure and ultra-high pressure water jetting. In many cases it has replaced the use of sand and slag blasting as it has the distinct advantage of capturing the material removed in a slurry instead of producing the hazardous dust associated with the previous technologies. For disintegration applications, water jetting has the advantage that the energy can be conducted in a flexible pipe and directed at the point where the energy is required. This has found possible applications in debarking (Krilov, 1983) and disintegration of wood (Mazurkiewicz, 1991). Other popular applications are for heat exchanger tube cleaning and unblocking sewer lines and as a cutting medium for profiling materials such as marble, steel and gaskets.

The Sugar Milling Research Institute (SMRI) has been investigating the potential of using water jetting as the cost saving breakthrough that the sugar industry needs. The project has become known as Prepex, referring to an alternative technique of preparation (PREP) and possibly a different approach to extraction (EX). This paper discusses only the preparation aspects of the process.

Development of the idea

The primary stimulation for exploring the possibility of shredding cane using water jets was a demonstration of the technology for surface preparation. The immediate question was that, if water can remove paint and rust so effectively, could it be used for shredding cane? This idea was first tested using a 12 MPa domestic pressure cleaner. Although the jet could not break through the rind of the cane it was thought that a higher pressure could potentially accomplish this. A 35 MPa hand-held industrial cleaner was successfully used to show that cane could be effectively shredded using water. Figure 1 shows how the fibres were separated by the water from the hand-held cleaner.

Figure 1. Cane shredded by hand-held industrial cleaner.

Following this initial successful test, consideration was given to further development and testing of the idea. The challenge of introducing an alternative technology into a sugar factory is that it must not adversely affect the performance of the factory if the existing technology were to be replaced. There are two parameters by which the preparation and extraction equipment of a factory need to be measured, namely, the power consumed (specific energy) and the extraction that can be achieved. At this early stage, capital costs were not considered as insufficient information was available to estimate these.

Specific energy

The energy absorbed by the preparation process is generally expressed as the power per unit mass flow rate of fibre, the units being kWh/tonne fibre. The installed power must exceed the average absorbed power to allow for variations in throughput. Renton (1974) indicated that the allowance varies from mill to mill, so installed power is not a good indicator. Moor (1994) attempted to quantify actual absorbed power; however, this varied depending on degree of preparation and shredder design. From the information presented by these and other authors it was estimated that a specific energy consumption for preparation needs to be equal to or better than 75 kWh/tonne fibre. In the case of water jetting, this specific energy would be the energy supplied to the pump per unit of fibre throughput. The energy that a pump transfers to the liquid pumped, assuming no losses, is given by the relationship:

$$P = pQ$$

where
P is the shaft power in the fluid
p is the change in pressure in the fluid
Q is the volumetric flow rate

The specific water consumption or water-to-cane ratio is:

$$Water-to-cane = \frac{Mass\ water\ used}{Mass\ cane\ shredded} = \frac{\rho Q}{\dot{m}_{cane}} = \frac{\rho Q}{\dot{m}_{fibre} / fc}$$

where
ρ *is the density of water*
$\dot{m}$ *is the mass rate*
fc is the fibre fraction in cane

Combining these equations, applying a factor to convert units to those traditionally used in a factory environment and working in terms of the ratio of water to fibre gives the equation:

$$Specific\ Energy[kW.h/tonne\ fibre] = pressure[MPa] * water\ to\ fibre / 3.6$$

Figure 2 shows this relationship for two pressures, 50 MPa and 100 MPa, which were considered to be in a realistic range for operation. Once the target specific energy is defined, the target fluid consumption is also fixed. This is the power supplied to the liquid and essentially the power that must be supplied for shredding. Some of this power is lost to fluid dynamic inefficiencies, noise and jet dispersion. Steps taken to reduce these losses will reduce the specific energy input requirements.

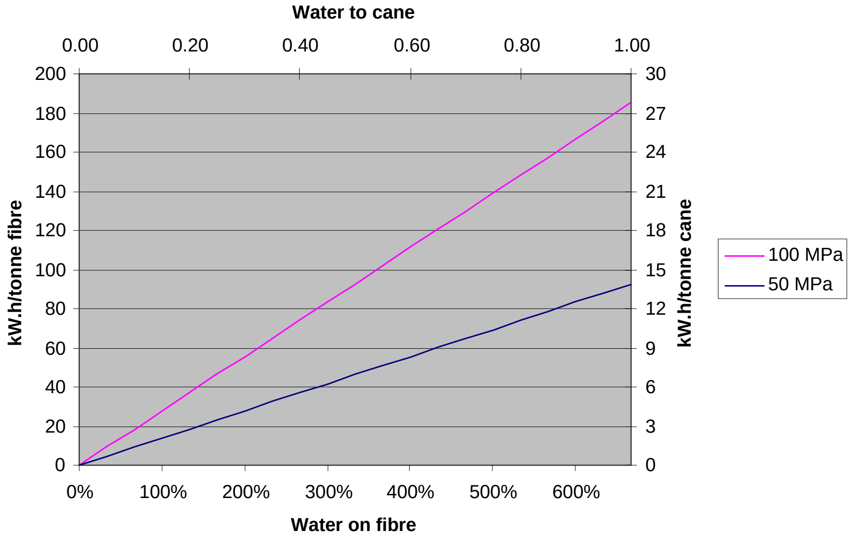

Figure 2. Relationship between water usage and energy consumed for a fibre content of 15% on cane.

Extraction

In a factory, any water that is added to the cane must be evaporated later. The addition of more water than is currently used for imbibition would result in an increased steam demand, together with a greater demand for boiler and evaporator capacity.

If clean water is used for water jet shredding, there has to be sufficient water left for imbibition to achieve extraction levels equivalent to those currently achieved. This places a limit on how much water can be used for shredding, as it is well known that lowering the imbibition rate will result in reduced extraction. Additionally, some concern has been raised that adding water during the shredding process will influence the brix profile in such a way that the desired extraction levels may not be achievable.

One way around this problem would be to use draft juice, or equivalent, as the cutting medium, rather than clean water. However, pumps capable of delivering the pressures and flow rates required are generally designed for use with clean water, such as for boiler feed water duty. Suspended and dissolved organic and inorganic solids and acid conditions are generally excluded by the pump manufacturers' specifications. Certain diaphragm (100 MPa) and some multi-stage centrifugal (up to 50 MPa) pumps are capable of handling more aggressive fluids, such as juice, at the required pressure but at a substantially higher capital cost.

Hence, it was important to determine the minimum water required per unit of cane shredded. It was expected that water consumption could be reduced by operating at a higher pressure, although this should have no impact on the specific energy consumption.

Laboratory experiments

Considering the fibre throughput, in the laboratory it was most convenient to weigh the cane and assume a constant fibre content. Many of the results are thus expressed in terms of water-to-cane ratio rather than water-to-fibre ratio. Excess cane was used in the tests to ensure that all the energy available was absorbed in the shredding of the cane. The water-to-cane ratio was thus based on the mass of cane shredded, which was assumed to be the difference between the starting cane mass and the mass of unshredded cane remaining after the test. However, it was not always easy to decide what portions of cane should be regarded as shredded, and so there was some level of uncertainty associated with this ratio.

Test rigs were constructed so that the energy and water requirements could be determined. A small rig, shown in Figure 3, was constructed for use with a 50 MPa, 17 L/min pump to quantify the operating parameters such as water and pressure requirements. The rig consisted of a slot where cane could be loaded and a chain-driven pusher arrangement to feed the cane past the nozzle. The width of the slot could accommodate a single stalk of cane, and up to three stalks could be stacked vertically. Various nozzles could be mounted above the end of the cane. The results from this first rig indicated that a higher pressure would be required to reduce the water requirement, and later tests were run with a loaned trailer-mounted 75 L/min pump that could deliver a pressure of 100 MPa. In addition, there was concern that the design of the first rig meant that substantial amounts of the high pressure water did not impact on the cane, and hence it was difficult to determine the water-to-cane ratio with much accuracy.

To address this, a larger test rig, shown in Figure 4, was constructed for use with the larger pump. A bottling plant conveyor of 180 mm width was used to convey the cane through the rig, with a second shorter conveyor overhead to help compress the cane before the nozzles to a height of about 300 mm. It was learned from the small rig that the cane needs to be presented to the water jets in an orderly and compact manner for maximum efficiency. The conveyors were driven by variable frequency drives in order to be able to vary the cane feed rate. The first tests used an array of fixed nozzles mounted on an eccentrically driven oscillating shaft mounted alongside the cane at a 45° angle. This was intended to ensure that the full height of the cane stack was covered by the water jets, but the high oscillation frequency required caused damage to the eccentric cam slot, and this approach was soon abandoned.

This array was replaced by three self rotating nozzles with a conical spray pattern. Although this approach was more successful, the conical shape of the spray pattern led to problems with the geometry. Essentially, with a close spacing of the nozzles, adjacent cones overlapped greatly, leading to reduced efficiencies, while a wider spacing meant that some cane nearest to the nozzles was not covered by the sprays. Various spacings and angles of the manifold were tested, but the conical spray geometry could not be made effective for an essentially rectangular block of cane.

The self-rotating nozzles were later replaced with a pneumatically driven nozzle assembly which had four arms, each with an attack tip with a fixed orifice to produce a cylindrical spray pattern with a radius of about 300 mm. To facilitate the removal of shredded cane, it was decided to place the assembly so that it could spray from the side. This caused problems in that the partly shredded cane was not supported and tended to fall out of the path of the jets, thus reducing the effectiveness of the water jets. The assembly was then orientated to spray downwards. Although this addressed the feed stability problem, adjustments had to be made to the calculations because the cane bundle was higher than it was wide and some water was not directed at the cane stalks. To maximise the use of the energy in the water jets it was decided that some cane should remain unshredded to ensure total absorption of the energy by the cane and not by the surface behind the cane. The question of how to separate the shredded and unshredded cane was never completely answered, and therefore total obliteration trials were later undertaken to prove that the cane could be completely shredded in one pass, although at the expense of lower efficiencies.

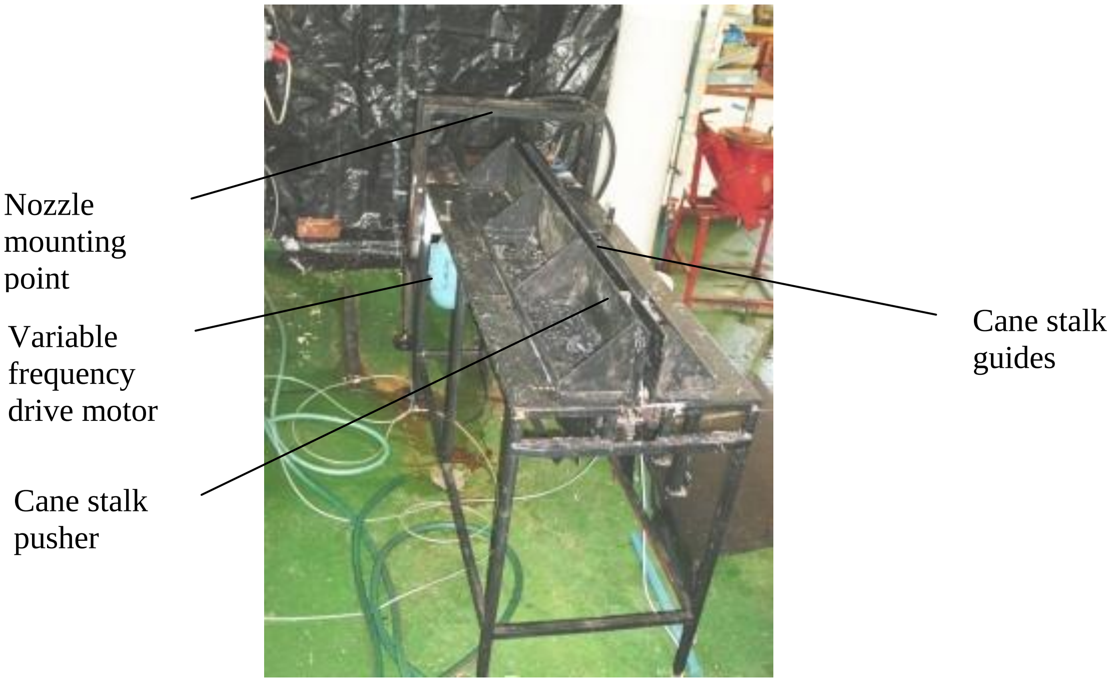

Figure 3. General layout of first Prepex apparatus.

Figure 4. Second rig for Prepex tests.

Parameters investigated

Specific energy

Specific energy (kW per tonne fibre per hour or kWh/tonne fibre) is a well understood quantity so it is useful to express the energy consumed by the Prepex process in these terms. For the water-to-cane ratios achieved of 0.45 at 100 MPa and 0.9 at 50 MPa the pump specific energy was approximately 90 kWh/tonne fibre, assuming a fibre content of 15%. Although this is above the initial target, this energy may be able to be reduced by using improved nozzle tip profiles and matching the absorbed and pump energies by manipulation of the cane feed rate.

Stand-off distance

The large mass of cane passing a nozzle arrangement can lead to a problem if the cane stalks tend to spring up and foul the nozzles, so it is essential that the distance between the nozzles and the cane needs to be maximised. The water jets, however, start to disintegrate after a distance causing a loss of concentration of the jet energy. These inefficiencies cause the energy consumption to become unacceptably high. The stability of a water jet depends on the geometry of the nozzle tip used. Tests using the hand-held nozzle showed that stand-off distances in excess of 400 mm could probably be accommodated. This was later tested using the test rigs that were constructed. In these trials, self-rotating nozzles with a conical flow pattern were used. It was difficult to quantify the effect of distance because other geometric issues came in to play. The increase in the distance between the target and the nozzle resulted in an increase in the area of coverage. The energy intensity therefore reduced and the amount of shredding was affected. In addition to this, the energy distribution across the line of the jet was not uniform, making it difficult to determine the actual amount of water used to shred the cane. Another aspect that influenced the experimental error was that the depth of cut, the stand-off distance and the width of coverage were all of the same order of magnitude, meaning that it was not clear how the true stand-off distance should be measured.

To further explore the effect of stand-off distance, a fixed nozzle was used (with no efficiency enhancements such as vortex breakers and a profiled orifice) and the cane moved through the jet at various distances. This nozzle could shred cane up to a stand-off distance of 100 mm, but no further. More efficient nozzles had previously demonstrated that cane could be shredded at much greater distances, suggesting that the nozzle design is critical to the success of the technology. This has been identified as a separate research area that could be pursued.

Penetration of water jet

It was found that the depth of penetration of the water jet into the cane bed has a non-linear relationship to pressure. This work showed that, if the energy efficiency criterion is to be satisfied, then the rate at which the cane is presented to the jets must be high enough to ensure that the energy in the water is efficiently absorbed.

To determine the effective depth of cut, cane was run under the four-arm nozzle assembly with a water pressure of 100 MPa. Part-way through the run, the water was stopped and the conveyor was then stopped. The resultant cut can be seen in Figure 5, showing that the water jets cut through only one layer of cane. Thereafter there was insufficient energy to cut into the layer of cane below. The rotating nozzle assembly thus cuts through two layers – one on the leading edge and one on the trailing edge.

This effect must be considered when optimising energy consumption. It is one of the inputs into the calculation of the balance between liquid flow rate and conveyor advance speed.

Figure 5. Stopped test indicating how cane is shredded in layers.

Liquid flow rate

The liquid flow rate is one of the parameters that determines the power supplied to the shredding process. This needs to be balanced with the rate at which cane is supplied to the process to ensure that as much of the energy in the water as possible is used to shred the cane. This is determined by the number of attack tips or nozzles and the flow rate per nozzle at each specific pressure.

Pressure

The lowest pressure suitable for the Prepex process is determined by the inherent strength of the cane. If the pressure is too low, there will be little or no shredding. An attack tip was mounted on a frame and a stalk of cane passed through the jet. The pressure was reduced until the water jet could no longer penetrate the stalk reliably. This pressure was found to be approximately 30 MPa. The advantages of using a lower pressure are that a simpler level of technology is required for the pumps and nozzles, and there is a lower risk of injury or damage in the event of a leak. The disadvantage is the increased amount of liquid required, which is especially a concern where water is to be used rather than juice.

There are advantages to using a higher pressure, in that the flow rate of the liquid may be much lower. This allows for smaller pipes and lower swept volumes in the pumps. The disadvantage, however, is that the technology required for the seals and pipes is more sophisticated.

At 100 MPa, the cane can be efficiently shredded with reduced amounts of water compared to the tests done at 50 MPa. The choice of pressure depends on the fluid chosen. Where water is used, the pressure needs to be as high as technically possible so that some water can be reserved for the extraction process. On the other hand, if juice can be used, increased evaporator load is no longer a consideration and thus larger flows can be used at a lower pressure.

Degree of preparation

A sample of cane prepared using the Prepex method is shown in Figure 6, giving an impression of very fine preparation. Unlike hammer mill prepared cane, where the cane is broken into fibres by a tearing action, the water jet prepared cane is subjected to shock waves similar to those described by Knežević (2002) when a water droplet strikes a flat surface. This would cause the cells to explode, thereby exposing different surfaces of the plant structure. The water jet shredding is essentially a combination of cutting and internal explosive disruption of the plant structure. The fineness of the preparation is affected by the cutting intensity and closely spaced cuts will yield a very fine preparation. Washing tests showed that the juice was easily removed from the prepared cane.

The addition of a shredding fluid complicates the measurement of degree of preparation. The sieving process described by Rein (1970) was found to be subject to operator bias. Any of the available washing techniques, such as preparation index (PI) and displacement rate index (DRI), will be affected by the shredding fluid and hence cannot be used.

Figure 6. A sample of Prepex-prepared cane.

The consolidated results from the trials conducted were documented by Loubser *et al.* (2008), and a summary of the range of measurements made is shown in Figure 7. From this, it can be seen that some configurations were able to shred all of the cane presented, although at higher than desirable water-to-cane ratios, apart from one trial. A number of trials were able to shred 80% of the cane at low water-to-cane ratios (0.30). It is believed that the start-stop and edge effects had some influence on this, as mentioned previously, and that a larger scale rig could produce results close to what would be necessary in a full-scale plant.

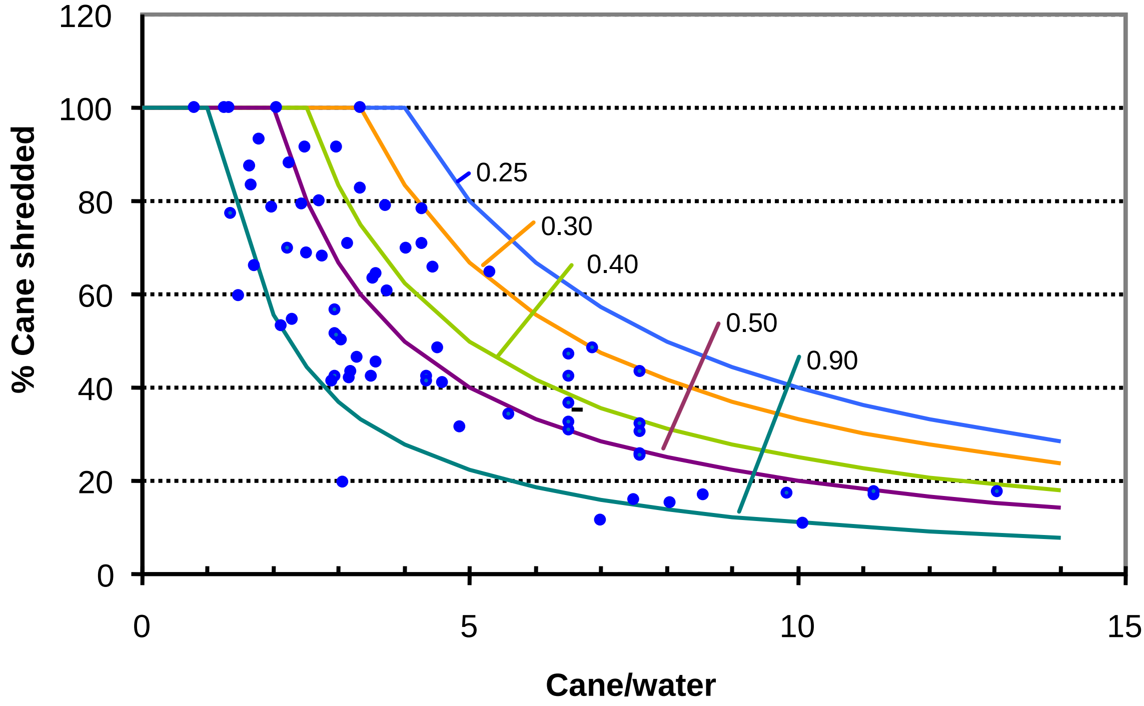

Figure 7. Summarised results from laboratory rigs. The x-axis represents the ratio of cane fed to the rig to water fed, while the curved lines represent various ratios of water to cane shredded.

Discussion

In the development of the Prepex process, the driving consideration was to save on maintenance costs and possibly capital cost without compromising the factory energy consumption. Many of the goals set out were based on meeting these objectives. If water is used for preparation, the ratio of water to cane shredded would have to be substantially better than 0.45, which is the approximate amount of water used for imbibition (300% imbibition on fibre based on 15% fibre in cane). This target also uses an amount of energy per tonne of cane similar to that of conventional knives and shredders (see Figure 2).

The test rigs to date have only been able to accommodate short runs. For optimum shredding conditions, some runs were as short as two seconds. The data acquired was thus affected by substantial start-stop and edge effects. To refine the efficiency data, a larger test rig with substantially longer running time is required.

The energy required to shred cane using liquid jets is comparable with that of conventional hammer mill preparation for the same degree of preparation, provided that care is taken to present the cane at an optimal rate. The presentation rate is important because a liquid jet will only shred a layer of cane that is moving. Once the liquid has passed through this layer, the energy is too diffuse to rupture the rind of subsequent layers.

The concept of Prepex was considered sufficiently innovative for a Patent Cooperation Treaty (provisional patent) to be applied for and granted, and national phase patents have been lodged.

Elements of a Prepex front end

In considering how the Prepex system could be implemented in a sugar cane processing factory, one can view the central part of the system as being the water jets. In addition to this, the design needs to cater for the cane presentation mechanism and the brix recovery system.

The functions of the components that are required for a Prepex front end are very similar to those in a conventional factory. Cane would be delivered in the normal way and the conventional spiller table approach would probably be adequate. Thereafter the feed rate of the cane would need to be regulated. The Prepex process is more sensitive to cane feed rate than conventional hammer mill shredding operations as the same power will be consumed whether or not cane is passing under the jets, whereas a hammer mill will consume less power if there is a gap in the cane. The cane then needs to be restrained or clamped before being shredded by the water jet as the efficiency of the system is dependent on the cane being held firmly when the water jet is applied. After shredding, the brix needs to be extracted from the fibre, after which the bagasse is dewatered. An outline of the process is shown in Figure 8.

.

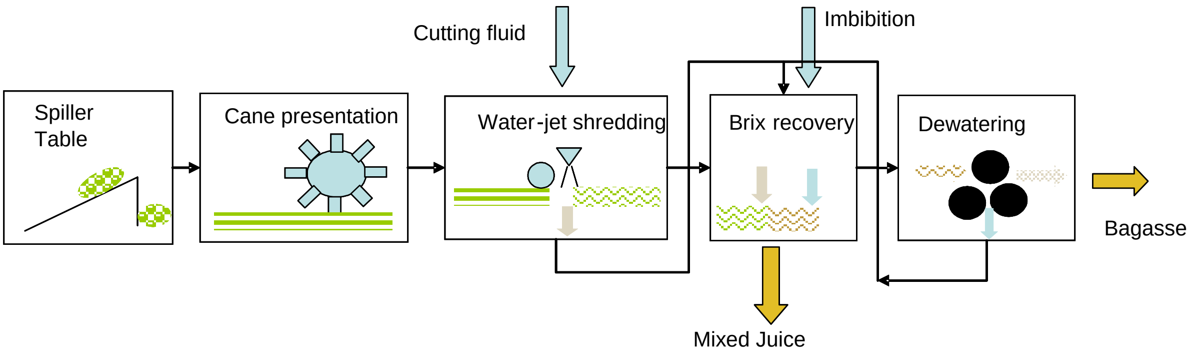

Figure 8. Outline of Prepex plant.

The economics of the process must consider capital and operating costs compared to conventional preparation methods. This would include energy considerations, both directly for preparation and any implications in terms of reduced mixed juice brix requiring extra energy for evaporation. Although preliminary economic models have been developed, more data from a larger scale pilot plant is necessary to more accurately determine energy and water requirements. In addition, the availability and costs of pumps suitable for pumping water or preferably juice at the flow rates and pressures required are a concern, and are likely to represent a substantial portion of the capital costs.

Conclusions

The use of water jets for shredding sugarcane was investigated by the SMRI. Sugarcane can be shredded by liquid jets, using a range of pressures and flow rates. One aspect that needs to be considered carefully is that liquid jets shred cane layer by layer. For the minimum specific energy to be consumed, it is important that the cane be presented at a rate which will match the energy input to the liquid jets.

The specific energy required for shredding cane using liquid jets will be similar to that used in a conventional knifing and hammer mill shredding operation, provided that the system balances energy input to the liquid with cane feed rate. In addition, the technology would eliminate the downtime required to replace hammers and knives.

The concept of using water or juice to shred sugarcane is technically feasible. The development process still requires input from the pump manufacturing community to select a cost effective pumping technology from both a mechanical and a materials point of view. In addition to this, further work will be required on a larger test plant to address scale-up issues, particularly in the cane stalk handling and shredded cane removal areas. Also, the edge and start-stop effects of the smaller rigs used in this work can be reduced on a larger rig.

REFERENCES

Edwards BP and Rogash G (1987). Ball mills for cane preparation. *Proc Aust Soc Sug Cane Technol* 9: 123-127.

Gómez AL, Cañón CF and Ramírez DE (2007). Hard faced welded tips in shredder hammers: Technical and economical performance. *Proc Int Soc Sug Cane Technol* 26: 1364-1372.

Gómez AL, Cañón CF and Ramírez DE (2008). Hard faced welded tips in shredder hammers: Technical and economical performance. *Int Sug J* 110(1314): 335-340.

Gómez AL, Valderrama CA, Velez CA, Ortiz JJ and Barrera G (2005). Wear in cane preparation machinery - some technical and economic considerations. *Proc Int Soc Sug Cane Technol* 25: 223-230.

Knežević KH (2002). High-velocity impact of a liquid droplet on a rigid surface: The Effect of liquid compressibility. Dissertation submitted to the Swiss Federal Institute Of Technology Zurich, 144 pp.

Koen A (1980). Reducing maintenance costs of shredder hammers and cane knives. *Proc S Afr Sug Technol Ass* 54: 45-47.

Krilov A (1983). Debarking of fibrous-barked hardwoods by ultra-high pressure water jets *Wood Sci* Technol 17: 145-158.

Loubser RC, Smith GT and Madho S (2008). PREPEX – Preparation for the future. *SMRI Technical Report* No. 2037(RC), 14 pp.

Mason V (1977). Implications of recent investigations on shredder hammer tip materials. *Proc Qld Soc Sug Cane Technol* 44: 255-259.

Mazurkiewicz M (1991). Disintegration of wood. United States Patent No. 5,035,362.

Moor B St C (1994). Review of cane shredding. *Proc S Afr Sug Technol Ass* 68: 162-165.

Moult JM (1980a). Performance testing of wear resistant materials used on shredder hammers. *Proc S Afr Sug Technol Ass* 54: 40-44.

Moult JM (1980b). Performance testing of wear resistance materials used on shredder hammers. *SMRI Technical Report* No. 1222, 58 pp.

Reid MJ (1996). The cost to the miller of soil in cane. *SMRI Technical Report* No. 1745, 9 pp.

Rein PW (1970). The interdependence of cane preparation, particle size, displaceability, and liquid holdup in fixed bed diffusers. *Proc S Afr Sug Technol Ass* 44: 64-70.

Renton RH (1974). A preliminary survey of power requirements for cane preparation. _Proc Int Soc Sug Cane Technol_ 15: 1575-1582.

Schlaudraff JE (1983). Testing of wear resistant materials on shredder hammers and knives. _SMRI Technical Report_ No. 1340, 40 pp.