MICROWAVE MODIFICATION OF SUGAR CANE TO ENHANCE JUICE EXTRACTION DURING MILLING

By

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Abstract

Mechanical shredders are used to rupture the storage parenchyma cells in the pith of the sugar cane stalk to facilitate extraction of the cane juice through the milling tandem. The cane shredder accounts for approximately 20% of the total energy balance in a sugar mill. Shredder hammers also wear quickly during the crushing season and need to be regularly maintained or replaced. These maintenance events interrupt the production schedule of the mill. Studies reported in the literature have revealed that applying intense microwave energy to wood can significantly reduce other processing energy requirements such as pulping or drying. Depending on the amount of energy applied, microwave treatment can reduce the density of Eucalyptus obliqua wood by up to 12%. This change in density reduces wood hardness by about 54% compared to untreated wood, resulting in substantial energy savings for processes such as reducing logs to wood pulp for paper manufacture. Other published studies have shown that microwave treatment significantly enhances the extraction of terpenes from caraway seed. Microwave treatment also increases essential oil yields (up to 30%) from peppermint and rosemary and reduces processing time. Cell rupture during microwave treatment was shown to play a significant role in enhancing extraction. This paper reports scoping studies in which microwave treatment was applied to small samples of sugar cane. Sugar juice diffusion was significantly enhanced by the microwave treatment and juice yields from crushing cane billets in a custom built press increased by a factor of 3.2 compared to the untreated control samples.

Introduction

Sugar is the second largest Australian export crop (Sugar Australia, 2004), after wheat, with total value of $861 million in 2008 (Australian Bureau of Statistics, 2010). Major export customers include Japan, Korea, Malaysia, Saudi Arabia, New Zealand, Canada, USA and Taiwan (Sugar Australia, 2004). Queensland accounts for about 95% of sugar production while northern New South Wales accounts for most of the remaining 5%. A very small quantity of sugar cane is grown in Western Australia. In 2009, 30 million tonnes of cane was crushed (Canegrowers, 2010) to yield over 4.5 million tonnes of raw sugar from 355 000 ha of land (Australian Bureau of Statistics, 2010).

About 80 to 85% of raw sugar is exported (Sugar Australia, 2004) and estimates suggest that the value of sugar production in 2010 may be in excess of $2.2 billion (Canegrowers, 2010). The sugar industry supports approximately 3760 agribusinesses in Queensland, northern New South Wales and Western Australia (Australian Bureau of Statistics, 2010) and generates more than 40 000 jobs (Sugar Australia, 2004).
Most Australian sugar cane is grown on family-owned and operated farms. When mature, the cane is harvested using mechanical harvesters and transported to sugar mills that are strategically located in the main sugar growing areas.

The objective of sugar milling is to extract as much sucrose from the cane stalk as possible. Figure 1 shows the general arrangement of the sugar juice extraction section of a typical sugar mill. Mechanical shredders, employing hammers, are used to rupture the storage parenchyma cells in the pith of the cane to facilitate extraction of the sugar juice through the milling tandem. Crushers normally consist of five rollers. All mills have several crushers arranged in tandem (Lobo et al., 2007).

Sugar mills use bagasse, the fibrous residue left after juice extraction, as a fuel source to drive the production system and provide some co-generation of electrical power during the crushing period (Lobo et al., 2007). In an economic study conducted by Lobo et al. (2007), the knives and shredder accounted for almost 50% of the total power requirements for the juice extraction train in a sugar mill with four mills.

In terms of overall energy requirements for the whole sugar production process in a mill, Siddhartha Bhatt and Rajkumar (2001) suggest that the cane shredder accounts for approximately 30% of the total energy balance in an entire sugar mill. Shredder hammers also wear quickly during the crushing season and need to be regularly maintained or replaced. These maintenance events interrupt the production schedule of the mill.

Clearly, reductions in the energy requirements and wear of the cane shredder could provide significant economic benefits to the industry. This paper briefly reviews the underlying structure of sugar cane and how microwave pre-treatment may interact with sugar cane to significantly soften the cane billets, therefore reducing the energy needed to process sugar cane and the accumulated wear on the juice extraction hardware. This review will be supported by a description of two small-scale scoping experiments conducted by the authors.

The structure of sugar cane stems

The sugar cane stem is divided into short, complex node regions and long, relatively simple internodes (Hussain et al., 2004). The node is where the leaf attaches to the stalk and where the buds and root primordia are found (Miller and Gilbert, 2006). The length and diameter of the internodes vary with varieties and growing conditions. In general, the inter-nodal length at the base of the cane is short but gradually increases up the stem (Miller and Gilbert, 2006).
A cross section of the inter-nodal section consists of epidermis, cortex (or rind), and pith tissue with embedded vascular bundles. The epidermis is a single superficial layer of cells formed by two cell types: the long cells and short cells that alternate with one another. The cortex consists of several layers of cells just inside the epidermis. The cortex cells are thick-walled and lignified, providing most of the mechanical strength of the cane (Miller and Gilbert, 2006). However, these cells contain less lignin and more hemi-cellulose than wood (Han and Wu, 2004).

The pith tissue consists of numerous vascular bundles that increase in number and decrease in size from the centre to the periphery. The mature sugarcane stem contains about 1500 vascular bundles, of which approximately 50% will be within the outer 1 mm of the pith tissue and 75% will be within the outer 3 mm of pith tissue (Hussain et al., 2004).

The peripheral vascular bundles contain xylem tissue but sometimes lack phloem tissue (Hussain et al., 2004). Xylem tissue conducts water and its dissolved minerals upward from the roots, and phloem conductive tissue transports plant manufactured nutrients and products, including sucrose, downward toward the roots (Miller and Gilbert, 2006). The vascular bundles near the centre of the stem tend to be larger and associated with parenchyma cells (Hussain et al., 2004). Parenchyma cells store sugar compounds as food for the plant (Salisbury and Ross, 1992).

Shredders are needed to fracture the hard cortex tissue and rupture the pith tissue for easy extraction of sugar juice during the crushing phase of milling. Energy savings could be made when the cortex tissue can be softened, the density of the cortex tissue can be reduced, and partial pith cell rupture can be induced before shredding commences.

**Experience with microwave treatment of wood**

The controlled application of intense microwave energy to green timber can directly manipulate moisture permeability, wood density and wood strength by rupturing cells without the need to use steam and long processing times (Vinden and Torgovnikov, 2000; Ximing et al., 2002). Lawrence (2006) has demonstrated that application of intense microwave energy can reduce the density of *Eucalyptus obliqua* wood by up to 12%, depending on microwave energy absorbed by the samples. Softwoods such as *Pinus radiata* can experience a more substantial change in density when exposed to the same energy levels (Lawrence, 2005).

This change in density associated with microwave treatment can reduce wood hardness by up to 54% compared to untreated wood (Awoyemi, 2003). Scott and Klungness (2005) showed that using microwave preconditioning on logs, before reducing them to paper pulp, reduced total energy consumption in the wood pulping process by 15%.

Manríquez and Moraes (2010) showed that the molecular structure of lignin is modified and hemi-cellulose begins to soften when the temperature rises above 55 °C. Above 100 °C these temperature effects become irreversible, resulting in significant reductions in mechanical strength of woody materials. Their study revealed a pronounced reduction of compressive strength of dry wood above 150 °C, which they attributed to the glassification of woody polymers (cellulose, hemi-cellulose and lignin). The final strength of their samples was only 35% of the initial room temperature strength. They also showed that these glass transformations occurred at much lower temperatures in moist wood samples.

Sugar cane cells contain lower amounts of lignin and greater amounts of hemi-cellulose than wood (Han and Wu, 2004); therefore it is reasonable to expect that there will be a more substantial strength loss in cane than in wood. It should also be noted that the moisture content of sugar cane is significantly higher than most wood species; therefore the glass transition process should occur at much lower temperatures than in wood. The water content of immature cane varies between 300%
and 900% on a dry weight basis along the stalk with the highest water content being at the top of the stalk. Mature cane has a moisture content of between 160% and 290% on a dry weight basis, depending on the variety. There is little variation on moisture content along the length of the cane at maturity (Liu and Helyar, 2003). The moisture content of fresh wood varies between 40 and 150% on a dry weight basis, depending on the species.

When the temperature of very moist plant materials exceeds 100 °C, steam can be generated inside the plant cells. Kanagawa et al. (1992) developed an effective method to improve the permeability of Japanese cedar wood (Cryptomeria japonica) by generating steam inside the wood cells. The method, which is called Local Steam Explosion, heats and softens wood in a chamber using high-pressure super-heated steam and then instantaneously exhausts the steam from the chamber. The sudden release of pressure boils free water in the wood cells. Permeability of the woody material is significantly increased due to the creation of local fractures in the wood cells. These microscopic fractures are produced when steam pressure inside the cells blasts tiny holes through the cell wall. There is usually a substantial strength loss associated with this rupturing of the cellular structure (Vinden and Torgovnikov, 2000).

The combination of material softening and local steam explosions suggests that pre-heating sugar cane using microwave energy should substantially reduce its mechanical strength and therefore reduce the energy required in the shredding phase of sugar production.

Microwave heating

Unlike conventional heating processes, microwave heating in small diameter cylinders, like sugar cane billets, occurs along the centre line of the cylinder rather than at the surface (Brodie, 2008a) and is accompanied by very rapid longitudinal moisture diffusion along the vascular conduits and to a lesser extent radially from the core to the surface (Brodie, 2007). These two important features of microwave heating should rupture the larger vascular bundles, the cortex, and the sugar storing parenchyma cells located near the centre of the stem, making it easier to extract sugar juice from the stems (Brodie, 2008b). Additionally, microwave heating will rapidly increase the temperature above the glass transition temperature of the various woody polymers (Manriquez and Moraes, 2010) and greatly reduce the crushing strength of the cane stem.

Microwave treatment of other plant materials

The most widely described application of microwave treatment in organic materials processing has been microwave assisted extraction (MAE). In this method, plant materials such as wood, seeds and leaves are suspended in solvents and the mixture is exposed to microwaves instead of conventional heating. Enhanced rates of extraction of plant based oils have been observed for a range of plant materials. In particular, Chen and Spiro (1994) examined the extraction of the essential oils of peppermint and rosemary from hexane and ethanol mixtures and found that yields were more than one third greater in the microwave assisted extractions. Saoud et al. (2006) studied MAE of essential oils from tea leaves and achieved higher yields (26.8 mg/g) than steam distillation (24 mg/g). Chemat et al. (2005) studied the extraction of oils from limonene and caraway seeds and found that MAE led to more rapid extraction as well as increased yields. Scanning electron microscopy of the microwave treated and untreated seeds revealed significantly increased rupture of the cell walls in the treated seeds. Also of relevance to its potential application to sugar milling, MAE in this study also led to a more chemically complex extract, which was thought to be a better representation of the true composition of the available oils in caraway seed.

Although less well described in the literature, an alternative approach for utilising microwave heating of plant based materials has been to treat the materials prior to extraction. In a study by Miletic et al. (2009), greenery and fruits of conifers were treated in a conventional
microwave prior to hydro distillation to extract essential oils. Both the kinetics of hydro distillation and oil yield were significantly increased for plant materials treated with microwaves.

Small scoping studies with sugar cane

In a recent scoping study, sugar cane segments (without nodes) sourced from a farm in Innisfail (North Qld) were exposed to varying levels of microwave treatment (2.5, 5, 7.5 or 10 minutes) in a conventional microwave oven operating at 2.45 GHz and nominally rated at 700 W prior to sucrose diffusion in water at 65 °C for 60 minutes. A calibration test has not yet been performed on this oven, so the actual microwave power output is unknown. Each cane sample was approximately 750–800 g. Triplicates at 5 microwave treatment times were undertaken.

Single factor analysis of variance and Tukey’s tests (95% confidence level) (Montgomery, 2005) demonstrated that microwave treatment of cane prior to diffusion extraction led to significant decreases in colour and significant increases in Brix, purity and pol. Qualitative observations indicated faster rates of extraction in the microwave treated cane; however decreases in juice quality was observed for long microwave treatment times. The optimal microwave treatment time was 5 minutes, which produced a 68% increase in Brix, a 58% increase in total dissolved solids, a 58% reduction in diffusion time, a 39% increase in Pol, and a 7% increase in juice purity compared with the control samples after 60 minutes of diffusion extraction.

In another simple scoping experiment, sixteen billets of cane, sourced from Mackay (via produce markets in Melbourne) were randomly allocated to one of four microwave pre-treatments (0, 90, 120, or 150 seconds in a conventional microwave oven operating at 2.45 GHz) before being crushed in a small press made from a manual screw-type car jack.

The microwave oven used in this experiment was calibrated using two water samples; one to act as a control in the laboratory and the other heated in the oven for 2 minutes. The microwave power was calculated by balancing the sensible and latent heats of the two samples to determine the energy absorbed by the microwave-treated sample. Based on this analysis, the microwave oven produced an average of 394.2 W of microwave power.

Plastic bags were used to hold the cane billets during microwave treatment. These bags were individually weighed prior to any other treatment. Cane billets were placed into individual plastic bags, weighed, and randomly allocated to one of the four microwave treatments (including the untreated control). Immediately after treatment, the cane billets were removed from the plastic bag, weighed again and pressed using the car jack crusher while still warm. The pressing force applied to each cane billet was the maximum force that could be manually exerted on the cane by the car jack crusher. The control samples were treated in exactly the same way, except they were not subjected to microwave treatment.

All the cane juice was collected into a pre-weighed beaker and weighed. The plastic bags were also weighed again after the cane was removed to determine the amount of juice that was expelled by the cane during microwave treatment. Total juice yield (pressed juice and any juice left in the plastic bags) was calculated as a percentage of the original mass of the cane billet. All weights were recorded to one tenth of a gram.

There was a significant increase in cane juice yield as a result of microwave treatment (Table 1). The 120 seconds treatment yielded the greatest amount of sugar juice; however there was no significant difference between the 90 second treatment and the 120 second treatment and there was a significant decline in yield as microwave treatment increased to 150 seconds (Table 1). This decline in yield as treatment time increased beyond 120 seconds was probably due to excessive drying of the cane billets. It has been shown elsewhere that microwave heating of moist materials
results in very fast moisture diffusion (Brodie, 2007) and rapid drying of cellulose based materials (Rozsa, 1995).

The samples that were treated for 90 seconds yielded approximately 3.2 times more cane juice than the untreated control samples. This additional yield from the microwave treated samples is probably due to several factors:

- significant softening of the woody polymers (cellulose, hemi-cellulosal and lignin) as the internal temperature of the cane billets rose above their respective glass transition temperatures (Manríquez and Moraes, 2010)
- rupture of the internal cellular structures in the cane due to localised steam explosions induced by microwave heating (Vinden and Torgovnikov, 2000)
- reduced viscosity of the sugar juice.

Table 1—Mean sugar juice yield, as a percentage of initial cane billet mass, after microwave treatment for four time periods.

<table>
<thead>
<tr>
<th>Treatment</th>
<th>Juice yield (%)</th>
</tr>
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<tbody>
<tr>
<td>Control</td>
<td>8.4 a</td>
</tr>
<tr>
<td>90 s</td>
<td>26.5 b</td>
</tr>
<tr>
<td>120 s</td>
<td>26.8 c</td>
</tr>
<tr>
<td>150 s</td>
<td>18.1 c</td>
</tr>
<tr>
<td>LSD (P = 0.05)</td>
<td>8.2</td>
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Note: Means with different superscripts are significantly different from one another.

Table 1—Mean sugar juice yield, as a percentage of initial cane billet mass, after microwave treatment for four time periods.

The average mass of each cane billet was 87 g; therefore the total energy associated with the 90 second treatment was approximately 0.112 kW-h/kg of cane. Microwave heating effects are notoriously non-linear. Often processing time can be greatly reduced as microwave power is marginally increased, so extrapolating these small scale results to industrial scale processing is fraught with potential errors. These studies should be followed up with a moderate-scaled pilot study.

It is understood that mechanical shredders were developed to achieve cellular rupture and improve sugar juice yields; however shredders do not soften the woody polymers or reduce the viscosity of sugar juice during treatment. Therefore it is hoped that microwave pre-treatment will significantly reduce the energy requirements and wear on shredding and crushing hardware used to process sugar cane.

Conclusions

This paper reports on some early thoughts and experiments that explore this new technique of pre-treating sugar cane. The research is on-going and further results will be published as they come to light. It can be confidently stated that microwave preconditioning of other materials prior to processing has resulted in beneficial changes in the mechanical properties of those materials. This significantly increases the yields of various plant-sourced products. Microwave pre-treatment of sugar cane has also produced significant increases in sugar juice yield and quality.

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REFERENCES


