ESTIMATES OF ETHANOL PRODUCTION FROM SUGAR CANE FEEDSTOCKS

By

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Abstract

This paper reports some observations regarding the potential production levels of ethanol from various feedstocks available in a sugar factory. The methods for calculating the yields of ethanol from sugar factory sources are investigated and a preferred method is described which could be used as a standard for comparing ethanol yields. The method determines the yields for the conversion of C6 sugars to ethanol based on the Gay-Lussac equation for fermentation. The potential feedstocks available to a sugar factory for the production of ethanol include raw sugar, C molasses (final molasses), B molasses, A molasses, evaporator supply juice (ESJ), secondary express juice and bagasse. The potential production of ethanol from each source is estimated (where possible) for Australia, based on the mean production data for five seasons from 1996 to 2000. The Australian cane sugar industry will find difficulty in supplying the potential market demand for the E10 petrol blend in Queensland with ethanol produced solely from final molasses. Alternative feedstocks will be required.

Introduction

The continued low production price for raw sugar on world markets has led to the investigation of alternative products for the Australian cane sugar industry with the overall aim of ensuring the long-term viability of the industry. One of the potential major alternative products (or co-products) for the cane sugar industry is the production of ethanol for various market sectors. Although the main focus of the attention in the media has been for the supply of ethanol for use as a blend in fuel for the domestic market in Australia, other major marketing opportunities exist for ethanol. These include the production of the appropriate grade ethanol for industrial chemicals and for alcoholic beverages for both the domestic and the export markets.

The properties of ethanol for use in fuel alcohol as a 10% ethanol blend (called E10) or as a stand alone fuel are well known and documented in many studies in Australia and overseas countries (Anon., 1994a; Anon., 1994b; Anon., 1994c; Rein, 1986; Rosillo-Calle and Cortez, 1998; and Swain, 2002). The use of ethanol in fuel blends for the internal combustion engine is well established and is proven practice in several countries including Brazil, USA, South Africa and Zimbabwe. There is also potential to substitute petroleum-based diesel with fuel ethanol. The advantages of the reduced harmful emissions from the tail pipe of diesel engines fuelled by ethanol in suburban/city environments has led to the entire bus fleet (over 220 buses) for the inner city of Stockholm in Sweden being replaced with buses fuelled with ethanol (~95% ethanol). Significant modifications are required to operate the diesel engines on fuel ethanol and the cost of these modifications (~$18,000) add approximately 10% to the overall capital cost of a passenger bus (Koerner, pers. commun. at the First Pacific Ethanol Conference. Brisbane.).
This paper does not assess the marketing aspects of ethanol, but focuses on the calculation of yields and potential production of ethanol from various feedstocks available in the Australian sugar cane industry.

Yields of ethanol

There are numerous methods for reporting the yields of ethanol. Yields are required for comparing fermentation processes and distillation technologies and for monitoring the performance of plant operations. Some yields can be misleading if care is not taken in determining precisely how the yield is derived.

Consider the yield of ethanol expressed as the volumetric production of ethanol per unit mass of molasses feed consumed in the fermentation process. For example, the yield for a particular process is say 250 litres of ethanol per tonne of molasses feed (Lavarack, 2001). This method of expressing ethanol yield is both simple and practical and is often preferred by both production and design personnel. The method is convenient for estimating the consumption requirements for molasses or the production rate of ethanol and aids in the sizing of plant and equipment (tanks, pipes etc.). However, the yield in litres of ethanol per tonne of molasses does not provide precise information concerning the fermentation efficiency since (i) the fermentable sugar levels in the molasses feed are not defined (and can vary depending on the feedstock selected), (ii) the grade of ethanol product is not specified (and the volume of product will vary depending on the water content and the temperature of the product), and (iii) the yield is net of ethanol losses in distillation (i.e. it does not differentiate between fermentation and distillation process losses of ethanol). Clearly, this expression of ethanol yield has its limitations in terms of the information it conveys regarding feedstock and product.

The simplest and most widely used method for reporting ethanol yields for the fermentation process is based on the updated Gay-Lussac equation and avoids some of these potential pitfalls.

Gay-Lussac yield

The updated\(^1\) Gay-Lussac equation for the fermentation of sugars to ethanol is as follows:

\[
\begin{align*}
\text{Reaction:} & \quad C_6H_{12}O_6 & \rightarrow & \quad 2 C_2H_5OH + 2 \text{CO}_2 \\
\text{Molar mass balance (kmol} \times \text{kg/kmol)} & \quad 1 \times 180.16 & \quad 2 \times 46.07 & \quad 2 \times 44.01 \\
\text{Mass balance (\%)} & \quad 100.00 & \quad 51.14 & \quad 48.86 & \quad (1)
\end{align*}
\]

The maximum theoretical yield from the Gay-Lussac equation is 51.14 mass units of ethanol produced per 100.00 mass units of dextrose (calculated in (1): \(100.0 \times (2 \times 46.07)/(1 \times 180.16)\)). However, Pasteur (Paturau, 1899) demonstrated in a famous series of experiments that the maximum practical yield is 48.40 mass units of ethanol per 100.00 mass units of dextrose because some of the dextrose is consumed in side reactions necessary for ethanol synthesis. Products of the side reactions are many and include glycerol, succinic acid, acetic acid etc. (Murtagh, 1999; Paturau, 1899). Consequently, the maximum practical yield from the Gay-Lussac equation is 94.6%\(^1\)

\(^1\) The original Gay-Lussac equation assumed that the feed is sucrose and the original equation is: \(C_{12}H_{22}O_{11} + H_2O \rightarrow 4C_2H_5OH + 4\text{CO}_2\). If the calculations are based on sucrose, the production of ethanol and carbon dioxide is increased by the stoichiometric equivalent, namely 1.053 (calculated from the ratio of the molecular masses of dextrose and sucrose: \((2 \times 180.16)/342.30\)).
Yields between 88% and 94% are considered good in practice (Webb, 1978).

The yield\(^2\) based on the Gay-Lussac equation is the preferred method for quoting ethanol yields for the fermentation process because it provides an unambiguous specification of the fermentation efficiency in which both the product (mass of 100% ethanol) and the feed (mass of fermentable sugar as dextrose) are well defined.

**Distillation efficiency**

The distillation efficiency is the ratio of the mass of ethanol in the final product to the mass of ethanol in the feed to the distillery. The losses of ethanol in distillation are small and distillation efficiencies are usually in the order of 98.5% or higher (Manohar Rao, 1997).

**Overall yield**

The overall ethanol yield is the product of the Gay-Lussac yield for fermentation and the distillation efficiency and is on a mass basis. Since the production of ethanol is normally reported (and sold) on a volumetric basis and overall production yields are preferred, the practice of quoting Gay-Lussac yields and distillery efficiencies are not often used in day to day factory operations. Other methods of reporting yields are applied.

**Other methods for reporting yields**

Several alternative methods for specifying ethanol yields are commonly used in day-to-day operations and include reporting:

1. ethanol on a volume basis as anhydrous product (for a specified temperature);
2. ethanol on a volume basis as a hydrous product (for a specified water content and temperature level);
3. ethanol yields (typically on a volume basis) per unit mass of molasses feedstock;
4. ethanol yields (typically on a volume basis) per unit mass of fermentable sugars (using a specified method for determining fermentable sugar levels);
5. ethanol yields (typically on a volume basis) per unit mass of fermentable sugars as sucrose;
6. ethanol yields (typically on a volume basis) per unit mass total sugars (including non-fermentable sugars); and
7. permutations of the above.

Table 1 lists fermentation yields using three methods and Table 2 compares the overall yields for some methods. Table 2 assumes the distillation efficiency is 99.0%. The density of ethanol at 20°C is used for all volumetric calculations in this paper\(^3\).

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\(^2\) The Gay-Lussac yield is also called the fermentation efficiency (Manohar Rao, 1997).

\(^3\) The density of anhydrous ethanol (100%) is 0.78934 Kg/L at 20°C and the density of hydrous ethanol (96.0 mass%ethanol water balance) is 0.80138 Kg/L at 20°C (Perry and Green, 1984). Ethanol is sometimes sold on the basis of the volume at 15°C (60°F). The density of anhydrous ethanol is 0.79389 Kg/L at 15°C (Perry and Green, 1984).
The level of fermentable sugars in the feed can be determined in several manners. A common procedure requires the determination of sucrose, fructose and glucose by either HPLC or GC analysis and conversion of all three moieties to an equivalent quantity of dextrose sugar. Empirical methods are also available. One empirical method determines the level of fermentable sugars by fermenting a known quantity of feed under specific conditions and measuring the loss in mass (through the evolution of carbon dioxide gas during fermentation). The level of fermentable sugars is determined from a calibration curve of the mass loss versus fermentable sugars. The calibration curve is obtained from the fermentation of known quantities of fermentable sugars under similar conditions. Care should be exercised with the results from one of these empirical methods since sucrose is the reference material and the fermentable sugars are reported as sucrose (and not dextrose).

Production levels for various feedstocks

The yields of ethanol from feedstocks available in a cane sugar factory are known to be almost independent of the purity of the feedstock (Rein, 1986). For the purpose of this paper, the overall yield for the production of ethanol for each of the nominated feedstocks is assumed to be 87.1%. This overall yield is regarded as good and assumes (i) a distillation efficiency of 99.0% and (ii) a fermentation efficiency of 88.0%. Reading from Table 2, the equivalent overall yield in litres of ethanol (100%) per tonne fermentable sugar is 564 L/t fermentable sugar.

The following raw materials are considered as potential substrates for the production of ethanol:

1. final molasses;
2. A and B molasses;

<table>
<thead>
<tr>
<th>Fermentation efficiency or yield based on Gay-Lussac equation, %</th>
<th>Fermentation yield in tonnes ethanol (100%) per tonne fermentable sugar in feed (as dextrose)</th>
<th>Fermentation yield in litres ethanol (100%) per tonne fermentable sugar in feed (as dextrose)</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>100%</td>
<td>0.511</td>
<td>648</td>
<td>Maximum Gay-Lussac yield, not achievable</td>
</tr>
<tr>
<td>94.6%</td>
<td>0.484</td>
<td>613</td>
<td>Maximum obtainable yield</td>
</tr>
<tr>
<td>94.0%</td>
<td>0.481</td>
<td>609</td>
<td>Good yields</td>
</tr>
<tr>
<td>92.0%</td>
<td>0.470</td>
<td>596</td>
<td></td>
</tr>
<tr>
<td>90.0%</td>
<td>0.460</td>
<td>583</td>
<td></td>
</tr>
<tr>
<td>88.0%</td>
<td>0.450</td>
<td>570</td>
<td></td>
</tr>
<tr>
<td>86.0%</td>
<td>0.440</td>
<td>557</td>
<td>Yields typical for fermentary designed in 1970s and 1980s</td>
</tr>
<tr>
<td>84.0%</td>
<td>0.430</td>
<td>544</td>
<td></td>
</tr>
</tbody>
</table>

Table 1—Comparison of ethanol yields for fermentation.

Volumetric yield is calculated assuming the density of ethanol is 0.78934 Kg/L at 20°C.
Table 2—Comparison of overall yields for ethanol distillery.

<table>
<thead>
<tr>
<th>Fermentation efficiency, %</th>
<th>Overall yield for distillery, %</th>
<th>Overall yield in tonnes ethanol (100%) per tonne fermentable sugar in feed (as dextrose)</th>
<th>Overall yield in litres ethanol (100%) per tonne fermentable sugar in feed (as dextrose)</th>
<th>Overall yield in litres ethanol (96%) per tonne fermentable sugar in feed (as dextrose)</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>100%</td>
<td>99.0%</td>
<td>0.506</td>
<td>641</td>
<td>668</td>
<td>Maximum Gay-Lussac yield, not achievable</td>
</tr>
<tr>
<td>94.6%</td>
<td>93.7%</td>
<td>0.479</td>
<td>607</td>
<td>632</td>
<td>Maximum obtainable yield</td>
</tr>
<tr>
<td>94.0%</td>
<td>93.1%</td>
<td>0.476</td>
<td>603</td>
<td>628</td>
<td>Good yields</td>
</tr>
<tr>
<td>92.0%</td>
<td>91.1%</td>
<td>0.466</td>
<td>590</td>
<td>615</td>
<td></td>
</tr>
<tr>
<td>90.0%</td>
<td>89.1%</td>
<td>0.456</td>
<td>577</td>
<td>601</td>
<td></td>
</tr>
<tr>
<td>88.0%</td>
<td>87.1%</td>
<td>0.446</td>
<td>564</td>
<td>588</td>
<td></td>
</tr>
<tr>
<td>86.0%</td>
<td>85.1%</td>
<td>0.435</td>
<td>552</td>
<td>575</td>
<td>Yields typical for fermentary designed in 1970’s and 1980’s</td>
</tr>
<tr>
<td>84.0%</td>
<td>83.2%</td>
<td>0.425</td>
<td>539</td>
<td>561</td>
<td></td>
</tr>
</tbody>
</table>

*Assumed distillation efficiency is 99.0%.

3. raw sugar;
4. evaporator supply juice (ESJ);
5. secondary express juice (SEJ) from the milling train; and
6. bagasse.

**Final molasses**

The most commonly used feedstock for the production of ethanol in the cane sugar industry is final molasses. The production data for final molasses in Australia are known (Anon., 2001). Table 3 lists the production of final molasses, raw sugar and cane harvested for the period 1996–2000. The five season mean for final molasses production is close to 1.1 million tonnes and corresponds to a final molasses production rate of 2.84 molasses% cane. The levels of fermentable sugar in final molasses for the whole of industry for the five-year period are not known since the analyses for the fermentable sugar levels are not routinely undertaken. It is assumed that the level of fermentable sugars in final molasses is approximately 45% based on anecdotal evidence. If all the available final molasses is fermented, the maximum potential production of ethanol from final molasses is in the order of about 280 million litres per year (based on the five year average from 1996 to 2000). The maximum production of ethanol (100%) from final molasses ranges from 220 million litres per year (1996 data) to 300 million litres per year (1997 data).
There are many supply commitments for final molasses and exports account for at least half of the annual production. Consequently, the scope for ethanol production from final molasses is considerably reduced. Some final molasses is required for animal feed. However, the residue from the fermentation of final molasses can be concentrated and is called CMS (condensed molasses solubles). CMS can provide a substitute for final molasses in some animal feeds.

**A and B molasses**

Potentially, both A and B molasses can substantially increase the supply levels of feedstock for fermentation compared to final molasses. B molasses is the primary feedstock used for the production of fuel ethanol in Zimbabwe (Rein, 1986).

The purity levels for A molasses and B molasses are not fixed and can be targeted to match (i) a particular boiling scheme for the production of a desired grade of sugar (e.g. Brand QHP, Brand 1 or Brand JA) and (ii) an exhaustion level for the molasses. SRI has undertaken simulations of pan stage operations to determine both the production rate and purity level for both A and B molasses for some grades of raw sugar products. These simulations are site specific. However, it is possible to generalise and assume approximate production rates and levels of fermentable sugar for both A and B molasses to determine the approximate production for ethanol from each of these substrates.

The potential production of ethanol from A molasses is approximately 1560 million litres per year. This calculation assumes that all A molasses is diverted to ethanol production, the level of fermentable sugars in A molasses is 60%, and the A molasses production rate is 12% on cane for the nominated five year period. Likewise the potential production of ethanol from B molasses is 680 million litres per year (assumes all B molasses is diverted to ethanol production, the level of fermentable sugars in B molasses is 52%, and the B molasses production rate is 6% on cane).

One important consideration for the determination of the potential use of A molasses or B molasses for ethanol production is the financial benefit in recovering the sucrose from the molasses as crystal sugar compared to the financial benefit from the production of ethanol.

**Raw sugar**

Raw sugar can be considered as a potential fermentation feedstock. The maximum potential ethanol production is about 3100 million litres per year (assumes that the raw sugar is Brand 1 and the level of fermentable sugars is 103.7% calculated: 98.5%×1.053). However, the folly of this is apparent if one assumes that the income from raw sugar is $1330 million (assuming $250 per tonne for the final product) compared to a potential total income of $1550 million for ethanol (assuming
$0.50 per litre). The additional investment and operating costs for distilleries could never be justified on this basis.

**Evaporator supply juice**

The potential production of ethanol from evaporator supply juice (or clarified juice) is similar to the sum of the ethanol production derived both from raw sugar and from final molasses and is approximately 3400 million litres per year. The main advantage of this feed source is that the costs for raw sugar manufacture are avoided. However, the production of ethanol is limited to the crushing season, unless some ESJ is concentrated and stored as liquor.

**Secondary express juice**

In this option, first express juice (FEJ) from the milling train is forwarded to the factory for raw sugar production and secondary express juice (SEJ) together with final molasses feeds the distillery. The production of ethanol from secondary express juice from the milling train is seen as desirable because SEJ contains higher levels of impurities and these impurities are sent directly to the distillery and may reduce some processing costs for the sugar factory. Increased levels of maceration are possible in this mode of operation and can increase the extraction of both sucrose and reducing sugars in the SEJ feed to the distillery. It is possible to split the juice from the milling train to optimise the purity and sugar levels in the two juice streams (viz. the feed to the sugar factory can comprise the juice from mill nos. 1 and 2 and the juice feed to the distillery is from the other mills). SRI has undertaken simulations in this regard and the outputs are site specific. Both the estimated flows and fermentable sugar levels for SEJ vary widely for the scenarios selected. Consequently, the estimated potential production level for ethanol from SEJ is highly variable.

The estimated ethanol production from SEJ is approximately 550 million litres per year and that from the final molasses (produced from the FEJ) is estimated to be 200 million litres per year (assumes all secondary express juice is forwarded to the distillery, the production level for SEJ is 45% on cane, the fermentable sugar levels in SEJ are 5.5%, the final molasses production level from FEJ is 2% on cane and the fermentable sugars in final molasses is 45%). The brix of the SEJ is low and can be less than that desired for some fermentation processes.

Several options exist for the production of ethanol from the fermentation of SEJ and final molasses (ex FEJ) and depend on the split of SEJ and FEJ flows in the milling train. These options will result in the reduced production of raw sugar, but some Brazilian factories apply this methodology to allow a mix of products to match market demand (Moreira and Goldemberg, 1999; Rosillo-Calle and Cortez, 1998).

**Bagasse**

The conversion of bagasse to C5 and C6 sugars can provide an additional source of carbohydrates for ethanol production. Although the technologies exist, no known commercial operation for the conversion of bagasse to ethanol is known to exist at present. In the USA, some full-scale production units for the conversion of fibre feedstocks to fermentable sugars are planned for the near future (Ibsen, 2002).

The production of ethanol from bagasse is viewed as having potential for the medium term. The potential production of ethanol from bagasse by fermentation is 290 million litres per year (assumes 13.5 fibre%cane and a conversion rate of 10 fermentable sugar%fibre). This estimate assumes that part of the bagasse production from the milling train is sent to ethanol production.
Other

SRI is presently evaluating the ZeaChem and other processes as a means to increase the potential production of ethanol from the available feedstocks. These other processes are reported by Bullock (2003).

Conclusions

The potential production levels of ethanol (100%) from the fermentation of various feedstocks available in a sugar factory are assessed for the whole of industry and are reported in Table 4.

<table>
<thead>
<tr>
<th>Feedstock</th>
<th>Approximate potential ethanol production, million L per annum</th>
</tr>
</thead>
<tbody>
<tr>
<td>Final molasses</td>
<td>280</td>
</tr>
<tr>
<td>B molasses</td>
<td>680</td>
</tr>
<tr>
<td>A molasses</td>
<td>1560</td>
</tr>
<tr>
<td>Raw sugar</td>
<td>3100</td>
</tr>
<tr>
<td>ESJ</td>
<td>3400</td>
</tr>
<tr>
<td>SEJ and final molasses from FEJ</td>
<td>750</td>
</tr>
<tr>
<td>Bagasse</td>
<td>290</td>
</tr>
</tbody>
</table>

The total petrol demands\(^4\) in 1989–1999 for Queensland and for Australia are 2887 million L/y and 16027 million L/y respectively (Anon., 2000). The required make of ethanol for the production of E10 blend for the Queensland market is approximately 290 million L/y and for the whole of Australia is 1600 million L/y. The Australian cane sugar industry will find difficulty in supplying the potential market demand for ethanol required for the E10 petrol blend in Queensland, with ethanol produced solely from final molasses. Alternative feedstocks will be required. The potential for the production of ethanol from secondary express juice should be explored as an additional carbohydrate source as it can increase the potential production to approximately 750 million litres per year, assuming all factories in Australia convert to this source. SRI is currently evaluating other production schemes to increase ethanol production from the available feedstocks.

Acknowledgments

I wish to thank SRI for the opportunity to publish these assessments into ethanol production.

REFERENCES


\(^4\) The demand is for leaded and unleaded petrol and does not include LPG or diesel.


