CHEMICAL ENGINEERING TRANSACTIONS Volume 24, 2011
Editor Sauro Pierucci
Copyright © 2011, AIDIC Servizi S.r.l., ISBN 978-88-95608-15-0 ISSN 1974-9791
DOI: 10.3303/CET1124061

Model and Optimisation of a Multi-Effect Evaporator of Sugarcane Juice: Energy Consumption and Inversion Losses

Daniela Galatro*, Elisa Verruschi, Roberto Guillen

Universidad Nacional Experimental Politécnica Antonio José de Sucre (UNEXPO)
Departamento de Ingenieria Quimica. Av. Corpahuaico entre Av. Rotaria y La Salle.
Barquisimeto, 03001, Venezuela.
cenipro@unexpo.edu.ve

A model simulation was developed using Pro II to estimate inverted sucrose rate in a triple effect evaporator of sugarcane juice. Dextrose and Fructose VLE parameters were included in the simulation. A set of correlations to estimate inversion sucrose rate based on empirical data compiled from qualified references were also included in the model. All results obtained by this sub-model were compared with experimental values and in all cases the relative error was under 5%. A Pinch analysis was performed by a module in Excel linked with Pro II. The minimum energy requirement of the system was estimated based on the vapour consumption calculated by Pro II. It was possible to reach near 20% of energy reduction, keeping the inverted sugars percentage under specification (max. 0.2% per each effect).

1. Introduction

During evaporation, a solution of cane juice is concentrated by the addition of heat.
A sugar evaporator is a heat exchanger (tubular calandria): the steam (hot side) surrounds the outside of the tubes and the juice to be evaporated is located inside the tubes. In a multi-effect evaporator, water is boiled in a series of vessels. The vapour boiled off in one vessel is used to heat the next one, except for in the first vessel, at the highest pressure, which requires an external source of heat.
Panpae et al. (2007) explained that the monitoring of total reducing sugar (reducing sugars plus hydrolysed sucrose) is important for the sugarcane agro-industry because “it may provide information for evaluation of the raw material and for the quality control of the sugar manufacturing process”. Sucrose inversion occurs by splitting this disaccharide into its components dextrose and fructose. They also summarized that “inverted sugar has a high affinity with water and is the cause of making products retain moisture”. In their work, the variation of the most important process parameters of sugarcane juice was studied and it was demonstrated that sucrose inversion is strongly dependent on pH, temperature and solid content. “Increasing solid content (lime juice), pH, and temperature during both heating and storage at room temperature, increased the rate of sucrose inversion”.

Please cite this article as: Galatro D., Verruschi E. and Guillen R., 2011, Model and optimisation of a multi-effect evaporator of sugar cane juice: energy consumption and inversion losses, Chemical Engineering Transactions, 24, 361-366
DOI: 10.3303/CET1124061

Control of inversion losses in evaporation consists of evaluating the ratio of reducing sugars to sucrose in the juice. Normal inversion losses in evaporation should not exceed 0.2% of sucrose as a maximum, according to Hugot (1986).

Saska (2008) mentioned that the development of general mathematical models and simulations are commonly assisted by simulation software packages such as ASPEN, Chemcad, HYSYS and others. He also described the software Sugars ®, as being readily available to the sugar industry. However, despite the benefits of having a software specific to sugar operation units, "the software has not become widespread because of its cost and complexity".

On the other hand, Hysys includes a workshop for a triple multi-effect evaporator of sugarcane. Each evaporator is modelled using a flash tank. Most of the process parameters of this work were taken from the mentioned Hysys workshop. The property package used in the Hysys simulation was Wilson/Ideal, and only the vapour-liquid equilibrium (VLE) for the binary mixture sucrose-water was analyzed. Dextrose and Fructose are not included in the components database of the software.

Abderafi and Bounahmidi (1994) obtained binary interaction parameters for the Peng Robinson, Lee-Kesler and NRTL thermodynamic method from experimental VLE data obtained for the binary mixtures sucrose-water, glucose-water and fructose-water. Analysis of the results of the parameters showed the Peng-Robinson model is the best in terms of the prediction of VLE.

A model was developed with Pro II to simulate a triple multi-effect evaporator of sugarcane juice. VLE of sucrose-water, dextrose-water and fructose-water was included in the model, being useful to estimate the sucrose inversion rate in each effect, based on the data obtained from qualified references.

1.1 Pinch Analysis

The first key concept of pinch analysis is setting energy targets, according to Kemp (2007). Targets obtained by pinch analysis are thermodynamic targets, showing what heating and cooling systems are correctly designed (heat exchanger network). In the presented work, a Pinch analysis module was performed in Excel ® and linked with Pro II to estimate the minimum energetic requirement.

2. Simulation model of the multi-effect evaporator

The chemical compounds considered in the simulation model were: water, sucrose and the inverted sugars: dextrose and fructose. Dextrose is available in the main database of Pro II (SIMSCI), however fructose must be set as user-defined compound, therefore all the physical and thermodynamic data of this component were included in the software. It was also necessary to modify the liquid-vapour equilibrium for Peng Robinson equation of state (EOS), adding the binary interaction parameters for dextrose-water and fructose-water. The required information is shown in the table 1.

Table 1: Physical and thermodynamic parameters included in the simulation

	Tc, K	Pc, atm	ω	VDV	ROG, mm	MW	Std. Density, kg/m^3	Liq.Solubility parameter, (cal/cc)$^{0.5}$
Sucrose	805.95	26.54	0.369	7.90	6.55 x 10^{-7}	342.30	1514.4	8.75
Dextrose	884.61	47.53	2.208	4.84	4.75 x 10^{-7}	180.16	1490	10
Fructose	884.35	47.67	2.210	4.84	4.75 x 10-^{7}	180.16	1490	10

Tc, Pc, ω were taken from Adberafi and Bounahmidi (1994).
VDV and ROG of Fructose were assumed same as Dextrose (Pro II database).
MW of Fructose is the same as Dextrose.
Where:
* Tc and Pc: Critical properties (temperature and pressure).
* ω: acentric factor.
* VDV: Van der Waals parameters.
* ROG: Radius of Gyration.
* MW: Molecular weight.

The binary interaction parameters for Peng – Robinson were taken from Adberafi and Bounahmidi (1994).
The process flow diagram of the simulation is shown in the Figure 1.

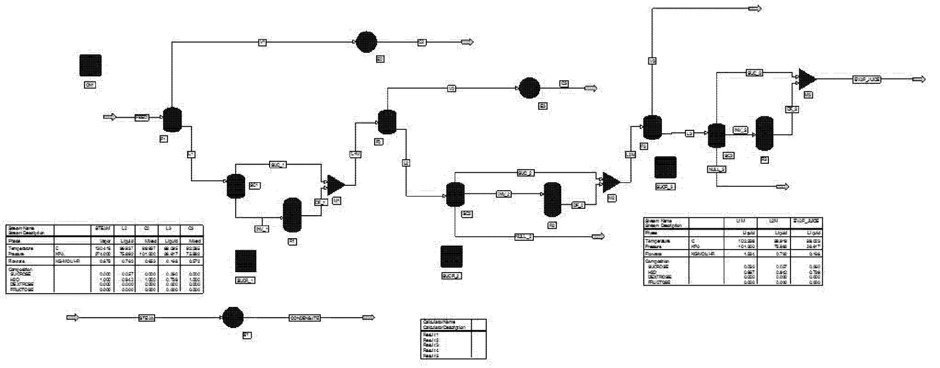

Figure 1: Process Flow Diagram for the Sugarcane Evaporator

The multi-effect evaporator was simulated using Pro II using three stages or effects. The evaporator consists of six operations: three effects modelled as flash tanks (unit operation "Flash" 1, 2 and 3) and three coolers (1, 2 and 3). The stream FEED (50 kg/h) is a liquid mixture of sucrose (30% wt) and water (70% wt) at 101.30 kPa of pressure. The heat used in the first effect is the heat calculated in the steam heat exchanger 1. The cooler 1 transforms saturated steam into condensate. The heat required in the next two stages is taken from the heat generated from the condensers 2 and 3 respectively. Coolers 2 and 3 condensate the outlet vapour stream of each flash (V1, V2 and V3 into C1, C2 and C3, respectively). The temperature of flash 2 and 3 is fixed and is equal to the temperature of the condensate C2 and C3 minus 3 °C, respectively. The liquid separated from each flash is sent to a Stream Calculator unit in order to separate the inverted sucrose from the sucrose. The inverted sucrose produced in the first stage is sent to the reactor (conversion type), where it is converted into dextrose and fructose (50:50) and is mixed with the sucrose juice to produce a stream which is sent to the next stage of evaporation. The simulation is analogue for stages 2 and 3. The flow rate of inverted sucrose and pH is calculated by the following expressions, based on the data compiled by Chi Chou (2000) and Hugot (1986):

$$pH = (0.0326T + 2.1613)\%INV-0.067 \quad (2)$$

$T < 105$ ºC: $\%INV=(0.0165\%S-0.6387)T+0.0991\ln(\%S)-0.4751$ (3)
$T \geq 105$ ºC:
$10\% S \rightarrow \%INV=3E\text{-}05T4 - 0.0155 T3 + 2.6459 T2 - 200.59T + 5697.1$ (4)
$20\% S \rightarrow \%INV=1E\text{-}05T4 - 0.0061T3 + 1.0343T2 - 77.624T + 2184$ (5)
$30\% S \rightarrow \%INV=-7E\text{-}06T4 + 0.0033T3- 0.5793T2 + 45.493T - 1333.6$ (6)
$40\% S \rightarrow \%INV=-1E\text{-}05T4 + 0.0047T3 - 0.8271T2 + 64.7T + 1890$ (7)
$50\% S \rightarrow \%INV=-1E\text{-}05T4 + 0.0061T3+ 1.0834T2 + 84.567T - 2465.7$ (8)

Where:
* T is temperature in ºC.
* % S: Weight percentage of sucrose (composition).
* %INV: Weight percentage of inverted sucrose per hour.

These correlations represent the percentage of inverted sucrose per hour in the evaporation system. This percentage depends on the temperature and pH in each effect. The correlations were obtained through Excel ® (trend-line tools, chart option), and all of them have a correlation coefficient “r” > 0.998. These equations were included in the statement of the Calculator 1 (Pro II).

The convergence was fixed by a controller that iterates until it reaches the concentration of 13% wt of water in the final juice (specification), varying the steam flow rate.

Solving the energy integration problem to minimize the utility consumption (heat flows) in the system was done by using Pinch analysis, according to Cortés et al. (2010). An integrated Excel ® spreadsheet is used to import the input (hot and cold streams) from the simulation and it gives back an output with the main curves where the minimum energetic requirements are estimated from.

3. Results

Pro II results are shown in table 2 and 3.

Table 2: Stream properties

Stream	FEED	STEAM	EVAPORATED JUICE
Rate, kg/h	50.000	12.223	17.242
Temperature, °C	101.324	130.418	89.022
pH	-	-	6.20
Pressure, kPa	101.300	274.000	26.617

Table 2: Stream flow rates

Stream	FEED	STEAM	EVAPORATED JUICE
Sucrose, kg/h	15.000	-	14.9742
Water, kg/h	35.000	12.223	2.2419
Dextrose, kg/h	-	-	0.0128
Fructose, kg/h	-	-	0.0128

The required steam flow rate to reach a juice concentration of 13% wt. of water was 12.2 kg/h.

Inverted sugars increase with the decreasing of pH, thus in the third effect the flow rate of dextrose plus fructose is 0.0256 kg/h, which is greater than the first and second effect. This amount of inverted sugars represents a 0.15%, less than the maximum percentage recommended of 0.2%, hence the pH control is important to minimize the sucrose losses. The pH drop between effects is usually 0.2. In this case, the pH drop between the second and third effect was 0.24.

The evaporation rate was 11.8 kg/h (effect 1), 10.3 kg/h (effect 2) and 10.7 (effect 3). The amount of sugar (sucrose + dextrose + fructose) in the evaporated stream of each effect was not significant (<0.0021% wt in the third effect).

All results obtained by this sub-model were also compared with experimental values and in all cases; the relative error was less than 5%.

A total of 8 hot and 3 cold streams were analyzed for the energetic thermal exchange analysis: Feed stream, inlet and outlet vapour stream, condensed flows and evaporator streams. Possible options of streams thermal combinations are shown in the composites curves (figure 2). The overlapping of the hot and cold streams indicates the maximum heat recovery of the process (or minimum utility requirements). The minimum temperature different was set as 10 °C (limit to establish the pinch point).

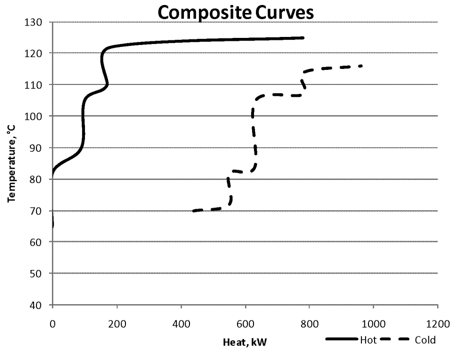

Figure 2: Pinch Analysis Composite Curves

The Pinch point was estimated at 114 °C. The minimum hot utility decreased from 8.4 to 6.7 kW (approximately -20 %), which means that there is an additional vapour consumption of 20% in the process that can be improved by using the new energetic configuration. The recalculated inversion loss using the new energetic configurations does not exceed 0.2%.

4. Conclusions

A simulation model was developed using Pro II to estimate inverted sucrose rate in a triple effect evaporator of sugarcane juice. This model was linked with a Pinch analysis spreadsheet in order to improve the energetic configuration of the heat exchanger network (vapour consumption).

The liquid-vapour equilibrium for Peng Robinson EOS was modified in order to add the binary interaction parameters for dextrose-water and fructose-water.

A set of correlations were obtained to estimate the percentage of inverted sucrose per hour in the evaporation system, as a function of the temperature and pH in each effect. These correlations were obtained through Excel ® and all of them have a correlation coefficient “r” > 0.998.

An additional vapour consumption of 20% in the process was estimated by Pinch Analysis. This consumption can be improved using the proposed energetic configuration. The re-calculated inversion losses using this new configuration did not exceed 0.2 % (recommended value).

The combination of process simulation (using a rigorous thermodynamic) and pinch analysis improve the energetic configuration of this heat exchanger network in terms of vapour consumption and inversion losses.

References

Abderafi, S and Bounahmidi, T 1994, Measurement and modeling of atmospheric pressure vapour-liquid equilibrium data for binary, ternary and quaternary mixtures of sucrose, glucose, fructose and water components. Fluid Phase Equilibria, 9, 337 – 351.

Chi Chou, C, 2000, Handbook of Sugar Refining: A Manual for the Design and Operation of Sugar Refining Facilities, Wiley-Blackwell, United States.

Cortés, M Verelst, H and Gonzales, E, 2010, Energy integration of multiple effect evaporators in sugar process production, paper presented to the 19th International Congress of Chemical and Process Engineering, Prague, 28 August – 1 September.

Hugot, E, 1986, Handbook of Cane Sugar Engineering, Elsevier, Amsterdam, the Netherlands.

Hysys workshop, 2000, Getting Started. <www.ualberta.ca> accessed 15.07.2009

Kemp, I, 2007, Pinch Analysis and Process Integration, A User Guide on Process Integration for the Efficient Use of Energy, Elsevier, Netherlands.

Panpae K, Jaturonrusmee W, Mingvanish W Nuntiwattanawong, C, Chunwiset, S., Santudrob K and Triphanpitak, S, 2007, Minimization of sucrose losses in sugar industry by pH and temperature optimisation. The Malaysian Journal of Analytical Sciences, 12, 3, 513 – 519.

Saska, M, 2008, Modeling Boiling House Operations with SuperPro Designer ®: Effects of Final Molasses Recycle and Double Magma Boiling, Sugar Journal, December, 12 – 17.