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Simulation of concentration and incineration as an alternative for vinasses' treatment

Simulación de la concentración e incineración como alternativa para el tratamiento de vinazas

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Abstract

In the present work the possibility of the concentration and incineration of the vinasse obtained in a Cuban rum factory was evaluated as an alternative for its treatment and to generate electricity. Simulation with ASPEN PLUS v7.2 was used as process analysis tool. A simulation model of the concentration process was obtained and models reported by the literature were used to simulate the incineration and generation of electricity. The model was validated with the real data of the process with a maximum validation error 5.5% for the total condensates. The necessary conditions were determined to increase the final concentration of the vinasse up to 60 ºBrix. The flow of concentrated vinasse was reduced by 48%, the problem of production shutdowns due to the unavailability of stillage storage was solved and 87 kg/h of potassium rich ash and 632 kW of electric power were obtained. Likewise, an economic analysis was carried out that demonstrated the feasibility of applying the proposed technology.

Keywords: simulation, vinasse, concentration, incineration.

Resumen

En el presente trabajo se evaluó la posibilidad de la concentración e incineración de la vinaza que se obtiene en la destilería de una ronera cubana como una alternativa para su tratamiento y para generar electricidad, haciendo uso de la simulación como herramienta de análisis de procesos. Mediante el empleo del simulador ASPEN PLUS v7.2 se obtuvo un modelo de simulación del proceso de concentración y se emplearon modelos reportados por la literatura para simular la incineración y la generación de electricidad. El modelo se validó con los datos reales del proceso con un error de validación máximo de 5,5% para la corriente de condensados totales. Se utilizó este modelo para determinar las condiciones necesarias para incrementar la concentración final de la vinaza hasta 60 ºBrix. Se logró reducir el flujo de vinaza concentrada en un 48%, se resolvió el problema de paradas en la producción debido a la no disponibilidad de almacenamiento de vinaza y además se obtuvieron 87 kg/h de cenizas ricas en potasio y 632 kW de energía eléctrica. Asimismo, se realizó un análisis económico que demostró la factibilidad de la aplicación de la tecnología propuesta.

Palabras clave: simulación, vinaza, concentración, incineración.

1 Introduction

The development of technological and chemical processes, in order to obtain products highly demanded, has resulted in negative phenomena such as those caused by industrial wastes (Pérez *et al*., 2017). From the fermentation and distillation of sugarcane molasses, the cane spirit is obtained. At the same time, vinasse is obtained in the distillation stage as a byproduct. Vinasse is one of organic residues with the greatest polluting effect on the flora and fauna over the planet.

In Cuba, ethanol distilleries cause, annually, a contamination referred as organic concentration, equivalent to 10 million inhabitants. The vinasse is a residual with the highest contamination due to its low pH (around 4), high temperature (between 100-105 ºC) and organic load (expressed as chemical oxygen demand, COD).

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If ethanol is produced from juices, a vinasse with 15-35 kg COD/m^3 is obtained and if it is produced from molasses, 60-80 kg COD/m^3 could be found. The volume of vinasse produced is, in general, 3-20 times greater than that of the ethanol produced, depending on the technology and represents approximately 90% of the original fermentation volume (Pérez, 2011).

The rum factory studied in this work is not exempt from these problems since the vinasse that is produced in the distillation process has a COD of 34,988 mg/L and a biological oxygen demand (BOD) of 28,130 mg/L, producing 408,000 L/d of vinasse (Pérez *et al*., 2017). A concentration system was installed in order to reduce this volume up to 62,400 L/d. The concentrated vinasse is sent to storage tanks until requested by another company. The system is designed to reach 60 ºBrix. Since the design concentration is not reached, the treatment system is incomplete because the collection times of the concentrated vinasse by other companies are greater than the planned 15 days per month and there is no alternative treatment for the vinasse after its concentration. For this reason, the total filling of the container tank has led several times to stop the production process. The total lost time between 2011 and 2017 was 377 days. This is equivalent to 11,321 m^3 of spirit not produced in this period, equivalent to 9,057,120 USD. A treatment applied to this residue can turn it into by-products with a certain economic value and at the same time, the negative impact on the environment caused by its incorrect disposal, can be reduced. There are many alternative treatments for this residual (Christofoletti *et al*., 2013), such as: fertirrigation (Mornadini and Quaia, 2013), recirculation to the fermentation stage to be used as dilution water of molasses (Castro, 2009), compost production (Conil, 2005), production of forage or torula yeast (Chanfón and Lorenzo, 2014), anaerobic digestion (Parsaee *et al*., 2019), concentration and desalination of vinasses (Pérez and Garrido, 2008), concentration and incineration of vinasses (Rocha *et al*., 2007; Akrama *et al*., 2015; Fukushima *et al*., 2019), fluidizing additive to raw cement pastes (Castro, 2009), oxidation with supercritical water (Arteaga *et al*., 2014) and electrocoagulation (Ojeda and Hing, 2010; Eco-potassium, 2015). After fertirrigation, animal feeding is the second alternative most widely used for vinasses in Cuba (Pérez *et al*., 2017).

The incineration of vinasses with high organic content is a way to obtain a positive return of energy, as well as the recovery of minerals. Before incineration, the vinasses are subjected to an evaporation process, where they are concentrated until a solids content of 60-65% is obtained to reach a caloric value of 9,218 kJ/kg (Rocha *et al*., 2007).

Once the vinasses are concentrated, they are subjected to their incineration in boilers designed for it. From the combustion of the vinasse, ashes with high potassium content (30-40% K_2O and 2-3% P_2O_5) are produced, which is recovered with sulfuric acid to form potassium sulfate (K_2SO_4), which is one of the main nutrients that form inorganic fertilizers (Larsson and Tengberg, 2014). 25-35 kg of fertilizer are obtained per 1,000 m^3 of incinerated vinasse (Arteaga *et al*., 2014).

The electrical energy that is obtained by incineration of vinasses, exceeds the electricity generated by the biogas produced by biodigestion in 2.5 times (Rocha *et al*., 2007). The problems reported with this method are the high energy requirements to concentrate the vinasses, as well as the consumption of part of the combustion energy in the evaporation of the remaining water (Arteaga *et al*., 2014). However, it has the advantages of reducing the environmental impact by diminishing the pouring of the vinasses after their treatment; the self-supply of the distillery and the concentration plant with the steam generated; the self-supply of electrical energy in the distillery and in the concentration plant and the surplus energy delivery to the national electroenergetic system (SEN); the use as fertilizers of ashes or their sale in the market and 72% savings in fossil fuel consumption and consequently, less CO_2 emissions (Alonso *et al*., 2016).

A comparison between concentration-incineration of vinasse and anaerobic digestion alternatives, both capable to reduce residual, generate steam and electricity, shows that the generation of vapor and energy in the concentration- vinasse incineration is higher. In addition, anaerobic digestion causes problems such as: appearance of residual sludge, danger of gas leakage, among others; while the concentration-incineration alternative is a "zero residual" technology and does not present this problem (Fukushima *et al*., 2019). As reported in Table 1 (Ramaiah and Chikhalikar, 1986), the generation of steam and energy in the concentration-incineration of vinasse is greater. Therefore, the concentration and incineration of vinasses was chosen as a study alternative due to the benefits obtained through their use.

The objective of the present research is: Evaluate the alternative of concentration and incineration for the treatment of vinasses and the possibility of electric power generation, using process simulation.

Table 1. Comparison between anaerobic digestion and concentration - incineration.

Distillery capacity (L/d)	**Steam generator/energy**			
	Anaerobic digestion (methane gas)		Incineration	
	Steam (kg/h)	Energy (kW)	Steam (kg/h)	Energy (kW)
30 000	3 230	255	7 760	625
45 000	4 840	385	1 163	940
75 000	8 060	640	1 939	1 565
100 000	10 750	855	2 585	2 090

2 Materials and methods

2.1 *Description of the technological process*

2.1.1 *Vinasse concentration*

This stage consists in extracting as much water as possible from the vinasse to reduce the volume of the residual. The vinasse concentration system contains four effects: EF-01 and EF-02 falling film evaporators, EF-03 forced circulation evaporator and EF-04 tube and shell condenser. In the first two, thermocompressors were installed, saving steam. From the second effect all, the equipment is connected to a 43.5 kPa vacuum pump, reducing the boiling temperatures. In this distillery, it is possible to concentrate the vinasse from 7 ºBrix to 35 ºBrix.

2.1.2 *Vinasse incineration and electricity generation*

Before to incineration, vinasse should be concentrated up to 60 °Brix and then the concentrated vinasse should be sent to a special boiler. In this way, the residual is eliminated by incineration and the energy contained in the flue gases could be used to generate steam. The ash resulting from the combustion of the vinasse, due to its high potassium content, can be treated and sold as fertilizer.

The steam generated, called live or direct, is fed to a backpressure turbogenerator where its expansion occurs, generating electricity that can supply part or all of the process demand. Exhaust steam can be used to heat the evaporation train and thus saves the fossil fuel used in a conventional steam generation.

2.2 *Use of simulation as a process analysis tool*

The process simulation predicts the behavior of a process using basic engineering tools, such as mass and energy balances, phase change and chemical equilibrium. If reliable thermodynamic data are available, the actual operating conditions are known, equipment models, among others, the actual behavior of the plant can be simulated.

The ASPEN PLUS v7.2 program was used to simulate the process. This simulator has a built-in model library for distillation columns, separators, heat exchangers, reactors, etc. Behavior models or properties are also in the model library. During the calculation, any missing parameter can be automatically estimated by various group contribution methods (Haydary, 2019).

In addition, the option of increasing the calculation capabilities, modeling of chemical reactions and unit processes, by programming in Fortran and Excel exists. This makes it possible to enter empirical formulas, correlations, kinetic equations, special design and operation equations, based on experimental or theoretical data, to different modules such as: reactors, distillation towers and pumps.

To simulate a process using ASPEN PLUS v7.2, the following steps were followed in general:

- Configure the simulation (units, report options, etc.).
- Select the components involved.
- Choose the method of evaluation of physical properties by components.
- Prepare the process flow diagram: blocks or modules and currents.
- Specify the required data of the streams.
- Specify the required data in the blocks or modules used.

2.2.1 *Methods for physical properties evaluation*

The recommended NRTL method for balancing water and organic substances was selected for the vinasse concentration. For the incineration, the IDEAL property package was selected as it is operated at high temperatures and the pressure does not exceed 200 kPa. Finally, for the generation of electricity in a Rankine power cycle, as water vapor is handled, IAPWS-95 was selected which is used to evaluate the thermodynamic properties of this compound (Aspen Technology, 2001).

2.2.2 Components selection

The composition of the vinasse depends on the characteristics of the raw material used in the production of ethanol (molasses in this case), the substrate used in fermentation, the type and efficiency of fermentation and distillation and the varieties and maturation of the cane (García and Rojas, 2005), hence its variability is high. The vinasse resulting from the distillation of fermented molasses has an elemental composition that contains all the wine components that have been swept away by water vapor, as well as quantities of residual sugar and volatile components.

The organic matter, expressed in mass percentage, present in a 55% solid vinasse could be distributed approximately as 6-7% of sugars, 5-7% of proteins and amino acids, 11-12% of gums, 9-11% of lignin and phenolic compounds and 9-10% of low molar mass compounds (Berón, 2005; Janke *et al*., 2015). A representative component was determined for each family. Sugars were represented by sucrose, proteins and amino acids by glutamic acid (Scull *et al*., 2012; Hidalgo *et al*. 2017), gums by glycerol (Montoya and Quintero, 2005) and the last two groups by fumaric and lactic acids respectively (García and Rojas, 2005).

The main inorganic components of the vinasse are shown in Table 2. The °Brix is the mass percentage of total soluble solids (SST) in a sugary product and for the simulation of the vinasses at 7 °Brix it is necessary to know which components are part of this group. According to Montoya and Quintero (2005) the soluble solids present in the vinasses comprise non-fermentable carbohydrates, salts, inhibitor compounds such as furfural and substances originated as a byproduct of yeast metabolism such as glycerol, propanol and lactic acid, which also inhibit reaction and growth rate.

Table 2. Main inorganic components of vinasse.

Component	Concentration (kg/m^3)
Phosphorous (as P_2O_5)	0.22
Potassium (as K_2O)	34.03
Calcium (as CaO)	5
Magnesium (as MgO)	5.4
Sulfates (as SO_4)	11.55

Table 3. Vinasse composition in the simulation.

Vinasse' component	Mass fraction
Sucrose	0.008273
L-Glutamic-Acid	0.007636
Glycerol	0.014636
Fumaric-Acid	0.012727
Lactic-Acid	0.012091
Diphosphorus-Pentaoxide (P_2O_5)	0.000022
Potassium-Oxide (K_2O)	0.003332
CALCIUM-OXIDE (CaO)	0.00049
MAGNESIUM-OXIDE (MgO)	0.000529
Sodium-Sulfate (Na_2SO_4)	0.001131
Ethanol	0.009134
Water	0.93

To determine the mass fraction of each component selected for a flow of 17,527 kg/h of vinasses at 7 °Brix, mass balances were performed by components. The amount of ethanol lost in the vinasse depends on the efficiency of the distillation columns, so a small fraction of ethanol, was also considered although it is not part of the Brix. The component that completes the composition of the vinasse was considered to be water. Table 3 shows the data introduced to the simulator to create the vinasse.

2.2.3 Calculation modules used for the simulation

The ASPEN PLUS v7.2 does not have evaporator modules, so to simulate this process it was necessary to adapt the unit operations that are carried out to the simulation program environment. The three evaporator vessels were simulated using the combination of the Heater and Flash2 modules. The first simulated the calender of the equipment where heat is transferred and the steam condenses. The second simulated the body of the equipment, where the separation of the evaporated stream and the concentrated fluid occurs. Both modules were connected by a heat current (HEAT STREAM) that represents the heat given by the steam when condensing in the Heater, to the Flash2 separator module.

The FSplit module allowed simulating all the flow divisions and steam extractions of the EF-01 and EF-02 (SPLIT2 and SPLIT3). The thermocompressors present in the Rum factory scheme were simulated by combining the FSplit of the extractions with a Mixer (TERMOC1 and TERMOC2).

For the simulation of recycle streams (ASPIR1 and ASPIR2), initially one stream was created to represent this recycle with its expected conditions and compositions. When advancing in the simulation, the unit that generates the recycle current was reached, the dummy current was eliminated and a real recirculation was included (Montoya and Quintero, 2005; Manente, 2017).

It is necessary to know the °Brix with which the vinasse comes out from each effect, in order to validate the model with a real factory data, and as a control parameter. Calculator blocks (CALCULATOR) were used for this purpose. Fortran code was used in CALCULATOR module in order to evaluate heat transfer area for each evaporator, evaporation ratio (evaporated water /heat transfer area) and economy (evaporated water / vapor consumption).

For the simulation of the incineration of concentrated vinasse, the model proposed by Palacios and Nebra (Palacios and Nebra, 2009) was used and for the generation of electricity that of the company Aspen Technology (Aspen Technology, 2015). To increase the lower heating value (VCI) of the vinasse and to facilitate its combustion, it is mixed with some additional fuel. The additional fuel is dependent on the type of technology to be used. In India, bagasse and coal are used (Balasubramanian and Kannan, 2016; Sakthivel, 2016) while in Brazil they use fuel oil as an additional fuel in an SSB-LCL burner from the German firm SAACKE. The fuel oil feed is 20% mass of the vinasse to be incinerated (Schopf and Erbino, 2010).

First, the existing concentration system was simulated to compare the results with the reality of the plant and validate the simulation model. Subsequently, the necessary modifications to achieve a concentrated vinasse with 60 °Brix and its incineration were simulated. To perform the simulation of the vinasse concentration up to 60 ºBrix, the design specifications block (DESING-SPEC) was used, taking as a manipulated variable the flow of heating vapor. The process information flow diagrams are presented in Fig. 1 and Fig. 2.

2.3 *Economic analysis*

The methodology suggested by Peters and Timmerhaus (2006) and applied by Lauzurique *et al.* (2017) was followed for the economic analysis. Prices and costs used for economic analysis are reported in Table 4. The calculation of the economic feasibility indicators was performed using the financial functions of Microsoft Excel.

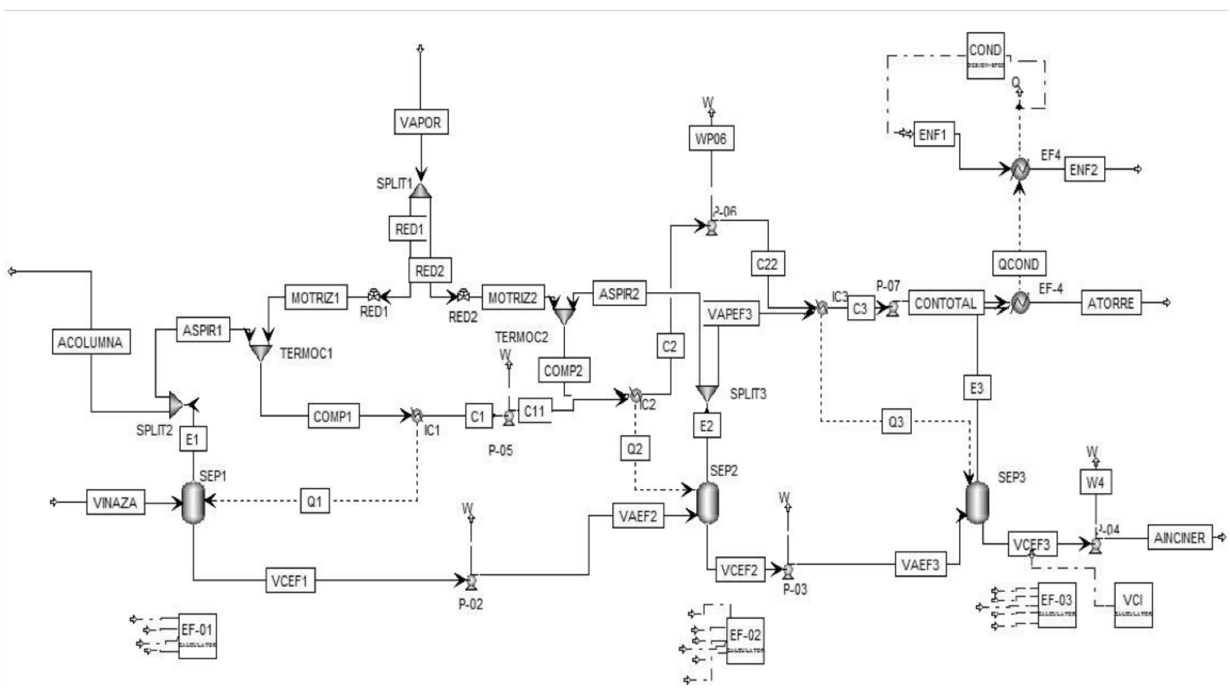

Fig. 1. Vinasse' concentration simulation.

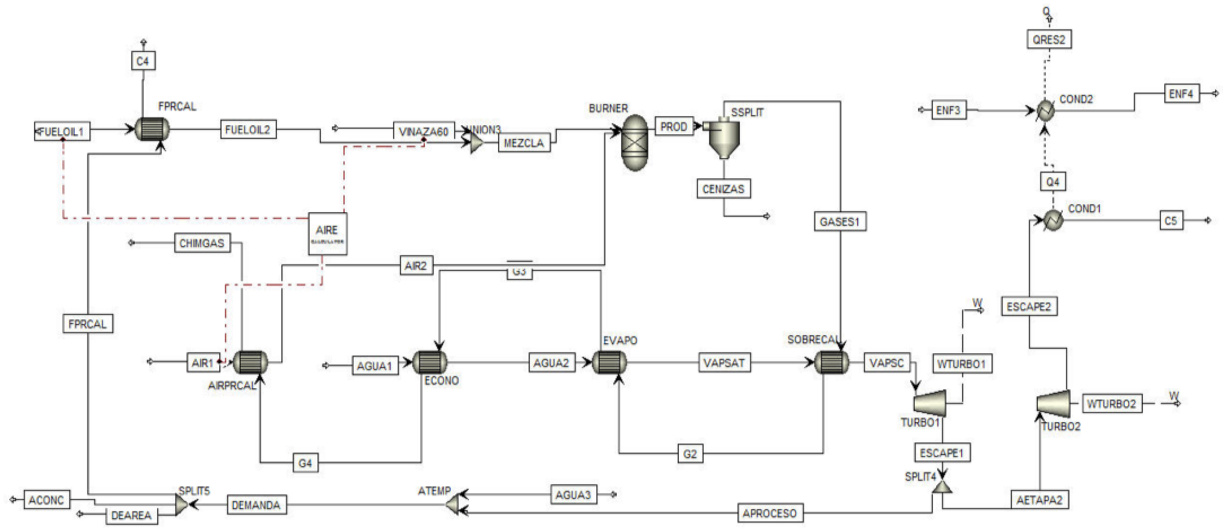

Fig. 2. Vinasse' incineration and electricity generation.

Table 4. Prices and costs for the economic evaluation.

Price/Cost	Unit	Value
Spirit price	$/L	0.8
Electricity price	$/kW h	0.16
Ash price	$/t	530
Water cost	$/m^3	0.11
Fuel oil cost	$/m^3	335.63

3 Results and discussion

Using the ASPEN PLUS v7.2 some properties were calculated to validate the simulated vinasse. These properties are shown in Table 5. It can be seen that the properties calculated by the simulator differ from those reported by the literature in less than 10% (except for DQO: 10-18%), so the model validation could continue. After the simulation of the concentration system, the results obtained by the simulator were compared with the actual process data. This comparison is shown in Table 6. As can be seen, the simulation model obtained represents the reality of the concentration process with a maximum relative error of 5.5%, for the total condensate flow. Therefore, the model can be used to evaluate the effect of changes in operating conditions, such as the increase in the concentration of vinasse at the exit of the system.

The operating conditions (brix exit and steam demand in each evaporator) were modified to concentrate the vinasses up to 60 ºBrix. The results obtained after these modifications are shown in Table 7. With the current steam generation capacity, the steam demand for the vinasse concentration up to 60 ºBrix can be satisfied. The sum of this with the other steam consumption (deaerator 1,476 kg/h and heating of fuel and molasses 200 kg/h) results in a total steam demand of 6,252 kg/h and the steam generator would be working at 89.31% of its capacity.

This is not a total solution to the problem of the vinasse, but by increasing the concentration to 60 °Brix the flow of concentrated vinasse is reduced by 48.28%. The vinegar storage tank of 1,200 m^3 capacity would be filled in 37 days, which represents an increase of approximately 18 working days before stopping the production by filling of the tank. These 18 days are equivalent to a complete production campaign that could be carried out additionally.

The condensates from the distillation workshop increased by 1,687 kg/h which is equivalent to 10.4% of the original flow. Now the cooling tower must process 17,795 kg/h of condensates extracted from the vinasse, 21,215 kg/h of cooling water and 10,500 kg/h of condensates from the distillation area, for a total flow of condensates to cool of 49,510 kg/h. This increase does not represent a problem since the tower was designed to process 90,000 kg/h (González *et al.*, 2018).

The average electricity consumption of the distillery is 80 MW per production campaign (18 days), so with the results shown in Table 8, the electricity demand is fulfilled by generating in a campaign 273 MW of electricity.

Table 5. Vinasse' validation.

Property	Reference	Value	ASPEN Plus	Relative error (%)
Density (kg/m3)	Parsaee et al., 2019	1 031	983	4.66
Heat capacity (kJ/kgK)	Parsaee et al., 2019	3.91	3.77	3.3
VCI (kJ/kg)	Zamora et al., 2016	6 811	6 395	6.1
DQO (g/L)*	Pérez et al., 2017	65-70	77	10-18

*For vinasses produced from molasses.

Table 6. Comparison of the results.

Parameter	Unit	Factory	ASPEN Plus	Relative error (%)
ºBrix exit EF-01	%	10-12	9.48	5.2
ºBrix exit EF-02	%	19 - 22	18.81	1
ºBrix exit EF-03	%	34 - 35	35.51	1.46
Evaporation EF-01	kg/h	8 340	8 557	2.6
Total Condensates	kg/h	15 262	16 108	5.54
Vinasse exit EF-03	kg/h	2 990	2 965	0.84

Table 7. Results for concentration of vinasse up to 60 ºBrix.

Parameter	Unit	ASPEN Plus
Brix exit EF-01	%	9.49
Brix exit EF-01	%	23.05
Brix exit EF-03	%	60.05
Heating steam to vinasse concentration area	kg/h	4 576
Steam sent to EF-01	kg/h	2 680
Steam aspirate EF-01	kg/h	6 011
Stem sent to EF-02	kg/h	1 896
Steam aspirate EF-02	kg/h	1 584
Stem sent to EF-03	kg/h	2 816
Concentrated vinasse 60 ºBrix	kg/h	1 748
Total condensates	kg/h	17 795

The difference is sold to the National Electric System (SEN) and as the demand is satisfied with the incineration of the vinasse, income is generated since the purchase of electricity is no longer necessary. The electricity produced in a 30,000 L of ethanol per day distillery, from a steam with similar conditions obtained from the incineration of vinasse was reported by Ramaiah and Chikhalikar (1986) as 625 kW. This value differs from the electricity production calculated with the simulator in 1.12%.

As can be seen in Table 8, the flow of combustion gases is high due to the high amount of combustion air necessary for the incineration of the mixture of oil and vinasse. The percentage of excess air was 300%. The cause of this phenomenon is explained because despite having concentrated the vinasse, it still has a significant amount of water in the mixture that comes with the vinasse and does not allow a high incineration temperature, making the combustion of organic components more difficult. In addition, it is necessary to control that the incineration temperature is less than 900 ºC (Schopf and Erbino, 2010) and this is achieved with the addition of % excess air.

Potassium represents 67% of the 87 kg/h of ashes obtained, which demonstrates the high concentration of this element in the vinasse and justifies the use of these ashes as natural fertilizers.

The temperature of the chimney gases is within the range referred by Palacios and Nebra (Palacios and Nebra, 2009) of 155-165 ºC, which demonstrates that the energy contained therein was used before being expelled to the atmosphere. The results of the economic analysis obtained are shown in Tables 9-10.

Table 8. Results for vinasse' incineration and electricity generation.

Parameter	Unit	ASPEN Plus
Electricity generation	kW-h	Stage 1: 491 Stage 2: 141 Total: 632
Ashes	kg/h	87
Combustion gases	kg/h	38 751
Chimney gases temperature	ºC	157
Tempering water	kg/h	385
Combustion air	kg/h	36 741
Fuel consumed	kg/h	349.6
Fuel saved	kg/h	25.4
Cooling water consumption	kg/h	1 360.75

Table 9. Sales and expenses.

	Value		Value
Electricity sales	737 771	Water consumption expenses	1 246
Ash sales	336 419	Electricity consumption expenses	4 346
Fuel oil savings	62 890	Salary expenses	221 400
Sales due to increased production	1 293 874	Maintenance	124 568
Annual Sales (AS)	2 430 955	Operation supplies	12 457
		Expenses associated with increased production	252 631
		Royalties and patents	12 333
		Annual Total Expenses (ATE)	628 980

Table 10. Economic indicators.

Indicator	Value
Annual sales (AS)	2 430 955
Total annual cost or expenses (ATE)	628 980
Annual cash income (ACI)	1 801 974
Annual total capital of investment (ATC)	7 521 589
Annual amount of depreciation (AD)	752 158
Annual amount of tax (AIT)	367 435
Net annual cash income (ANCI)	1 434 539
NPV ($)	583 876
IRR (%)	13.87
PBP (years)	4.17
DPBP (years)	5.24

NPV: Net present value, IRR: Internal rate of return, PBP: Payback period, DPBP: Discounted payback period

Environmental problem can be solved, treating the vinasse in the distillery and as can be seen in Table 10, high income values can be obtained. The alternative is economically feasible. This is explained because the NPV, being an income alternative, took a positive value (583,876.56 USD), the IRR obtained (13.83%) is greater than the interest rate taken for the calculation (12%) and the PBP are less than 5 years (4.17) and the DPBP is 5.24. As the capital invested is recovered in a shorter time than the planning horizon of the project (10 years), the project shows a high liquidity.

Conclusions

The vinasse concentration process of a Cuban distillery was simulated, validating the simulation model, with real data of the distillery concentration process, showing a maximum relative error of 5.5%, Therefore, the model can be used to evaluate the effect of changes in operating conditions, such as the increase in the concentration of vinasse at the exit of the system.

The operating conditions were modified to concentrate the vinasses up to 60 ºBrix. These modifications were simulated using the previously obtained and validated model for the concentration process, and the simulation of the incineration of the vinasses concentrated at 60 ºBrix and the generation of electricity, using models validated by the literature. The flow of concentrated vinasse was reduced by 48%, the problem of production shutdowns due to the unavailability of stillage storage was solved and 87 kg/h of potassium rich ash and 632 kW of electric power were obtained.

The proposed treatment alternative was technically economically evaluated, obtaining a NPV of 583,876.56 USD and an IRR of 13.87% for an investment cost of 7,521,589 USD, recovering the investment in 5.24 years.

References

Akrama, M., Tan, C.K., Garwood, R., & Tha, S.M. (2015). Vinasse - A potential biofuel - Cofiring with coal in a fluidised bed combustor. *Fuel 158*, 1006-1015.

Alonso, D., Garrido, N., Pérez, O. y Zumalacárregui, L. (2016). Alternativas tecnológicas para reducir el volumen de las vinazas de la industria alcoholera y su tratamiento. *Centro Azúcar 43*, 70-79.

Arteaga, L., Carvajal, G., y Bolaños, O. (2014). Proceso de producción de etanol a partir de melazas. Disponible en: aunartech.aunar.edu.co/images/revista/pdf/junio-2013/008.produccion-de-etanol.pdf. Accesado: 16 noviembre 2018.

Aspen Technology. (2001). Aspen physical property system 11.1. In: *Physical Property Methods and Models* (pp. 436). USA: Aspen Technology

Aspen Technology. (2015). Steam cycle simulation - Aspen Plus v8.6. USA: Copyright © 1981 - 2015 Aspen Technology, Inc.

Balasubramanian, S., & Kannan, P. (2016). Spent wash/vinasse/stillage incineration technology. 16-18 August. Durban, SouthAfrica: *89th Congress of the South African Sugar Technology Association*.

Berón, G. (2005). Usos alternativos de las vinazas de acuerdo con su composición química. *Tecnicaña 9*, 15-19.

Castro, G. (2009). El tratamiento de las vinazas - la recirculación. *Publicaciones e Investigación 3*, 52-58.

Chanfón, J.M. y Lorenzo, Y. (2014). Alternativas de tratamiento de las vinazas de destilería. Experiencias nacionales e internacionales. *Centro Azúcar 41*, 56-67.

Conil, P. (2005). Manejo de vinazas: metanización y compostaje, aplicaciones industriales. *Tecnicaña 9*, 26-30.

Christofoletti, C.A, Escher, J.P, Correia, J.E., Urbano, J.F., & Fontanetti, C.S. (2013). Sugarcane vinasse: Environmental implications of its use. *Waste Management 33*, 2752-2761.

Eco potasio. (2015). Sustentabilidad en el uso de vinaza. Disponible en: www.ecopotasio.com/es/q_hacemos.html. Accesado: 13 abril 2018.

Fukushima, N.A., Palacios-Bereche, M.C., Palacios-Bereche, R., & Nebra, S.A. (2019). Energy analysis of the ethanol industry considering vinasse concentration and incineration. *Renewable Energy 140*, 1-49.

García, A. y Rojas, C. (2005). Posibilidades de uso de la vinaza en la agricultura de acuerdo con su modo de acción en los suelos. *Tecnicaña 9*, 3-13.

González, B., Pérez, O., Zumalacárregui, L., y Lorenzo, J. (2018). Integración de la red de agua en una ronera cubana. *UCE Ciencia Revista de Postgrado 6*, 1-13.

Haydary, J. (2019). *Chemical Process Design and Simulation: Aspen Plus and Aspen Hysys Applications*. John Wiley & Sons, Inc., USA.

Hidalgo, K., R. Bocourt, R., Mora, L., & Albelo, A. (2017). Physical-chemical and microbiological characterization of the concentrated vinasse from alcohol distillery. *Cuban Journal of Agricultural Science 51*, 459-469.

Janke, L., Leite, A., Nikolausz, M., Schmidt, T., Liebetrau, J., Nelles, M., & Stinner, W. (2015). Biogas production from sugarcane waste: assessment on kinetic challenges for process designing. *International Journal of Molecular Sciences 16*, 20685-20703.

Larsson, E., & Tengberg, T. (2014). Evaporation of vinasse: pilot plant investigation and preliminary process design. Master's Thesis, Chalmers University of Technology, Göteborg, Sweden. Disponible en: studentarbeten.chalmers.se/publication/195305-evaporation-of-vinasse-pilot-plant-investigation-and-preliminary-process-design. Accesado: 7 marzo 2019.

Lauzurique, Y., Zumalacárregui, L. Pérez, O. y Rojas, D. (2017). Simulación de la destilación extractiva con sales para la obtención de etanol deshidratado. *Revista Mexicana de Ingeniería Química 16*, 1055-1066.

Manente, G. (2017). Modeling, simulation and optimization of energy systems using Aspen Plus. University of Ljubljana, Slovenia. Disponible en: businessdocbox.com/Green_Solutions/74198596-Modeling-simulation-and-optimization-of-energy-systems-using-aspen-plus-giovanni-manente-university-of-padova.html. Accesado: 10 julio 2018.

Montoya, M.I. y Quintero, J.A. (2005). Esquema tecnológico integral de la producción de bioetanol carburante. Tesis de Grado, Universidad Nacional de Colombia, Colombia. Disponible en: www.researchgate.net/profile/Julian_Quintero/publication/38975441_Esquema_tecnologico_integral_de_la_produccion_de_bioetanol_carburante/links/53ceb3e50cf2fd75bc58f0f7/Esquema-tecnologico-integral-de-la-produccion-de-bioetanol-carburante.pdf. Accesado: 27 mayo 2019.

Mornadini M., & Quaia, E. (2013). Alternativas para el aprovechamiento de la vinaza como subproducto de la actividad sucroalcoholera. *Avance Agroindustrial 34*, 1-12.

Ojeda, E., Hing, R. (2010). Estudio del proceso de electrocoagulación de la vinaza empleando electrodos de aluminio. *Tecnología Química 30*, 38-47.

Palacios, R., & Nebra, S. (2009). Thermodynamic modeling of a cogeneration system for a sugarcane mill using Aspen Plus, difficulties and challenges. 5-20 November. Gramado, Brazil: *20th International Congress of Mechanical Engineering.*

Parsaee, M., Kiani, M., & Karimi, K. (2019). A review of biogas production from sugarcane vinasse. *Biomass and Bioenergy 122*, 117-125.

Pérez, I., Garrido N. (2008). Tratamiento de efluentes de la industria alcoholera: ventajas y desventajas. *Ingeniería Química 455*, 148-53.

Pérez, O. (2011). Modelación, simulación y análisis con fines energéticos de destilerías de etanol hidratado. Tesis de Doctorado en Ciencias Técnicas, Instituto Superior Politécnico "José Antonio Echeverría", Cuba.

Pérez, Y., Pérez, O. y Zumalacárregui, M. (2017). Caracterización química, física y microbiológica de dos vinazas cubanas. *EIA 14*, 29-43.

Peters M.S., & Timmerhaus K.D. (2006). *Plant Design and Economics for Chemical Engineers*. McGrall-Hill, USA.

Ramaiah, N., & Chikhalikar, V. (1986). Energy generation through distillery effluent treatment. 21-31 August, Jakarta, Indonesia: *XIX Congress of International Society of Sugar Cane Technologists.*

Rocha, M.H., Silva, E.E., & Venturini, O.J. (2007). Life cycle analysis of different alternatives for the treatment and disposal of ethanol vinasse. 29 July - 2 August. Durban, South African: *XXVI Congress of the International Society of Sugar Cane Technology.*

Sakthivel, T. (2016). Spent wash incineration technology. AIDA: New Delhi. Disponible en: www.aidaindia.org/pdf/hyderabad-seminar/15.pdf. Accesado: 29 junio 2018.

Schopf, N., & Erbino, P. (2010). Thermal utilisation of vinasse as alternative fuel. 7-11 March. Veracruz, México: *XXVII Congress of the International Society of Sugar Cane Technology.*

Scull, I., Savón, L., Gutiérrez, O., Valiño, E., Orta, I., Mora, P., Noda, A. (2012). Composición físico química de mostos concentrados para su evaluación en dietas destinadas a animales. *Revista Cubana de Ciencia Agrícola 46*, 385-389.

Zamora, G., Mistretta, M., Peralta, F., Gutiérrez, C., Golato, M., Paz D., Cárdenas, G. (2016). Caracterización energética de vinazas de caña de azúcar como posible biocombustible para calderas de vapor bagaceras. 11-17 Junio, Argentina: *XXXIX Reunión de Trabajo de la Asociación Argentina de Energías Renovables y Medio Ambiente.*