ENCIT-2018-XXXX
A CASSAVA BIOREFINERY - A MASS AND ENERGY BALANCE

Caryl A. B. Schutze
Waldir A. Bizzo
Universidade Estadual de Campinas, Cidade Universitaria Zeferino Vaz - Barao Geraldo, Campinas - SP, 13083-970
cbschutze@fem.unicamp.br,bizzo@fem.unicamp.br

Abstract. *This paper aimed to evaluate the technical requirements of mass,energy and equipment in order to create a mixed cassava mill that produces both ethanol and starch from the cassava root much like a modern sugar cane mill produces both ethanol and sugar. In order to properly create a parallel between modern Brazilian sugar cane mills and the proposed cassava mill, a complete characterization of the cassava plant residue as possible solid fuel source for the industrial process was made. Also, as the mill would be considered a complete and mid scale biorefinery, an estimate was calculated for the probable electric energy by-product that would in turn be sold to the national market.*

Keywords: *Cassava, Ethanol, Starch, Renewable Energy*

1. INTRODUCTION

Energy, a source of wealth in its abundance and a heavy economic burden in its absence, represents one of the corner stones of our modern world. The ever expanding need for reliable fuel sources as more and more human beings rise out of subsistence living is one that comes in conflict with our planets diminishing tolerance to our CO_2 emissions. With this in mind, the search for new renewable energy sources has become the beacon of any modern economies. Agriculture and its residues are again seen with "energetic" eyes as the world looks to biomass as a palliative medicine to an over heated Earth. Biomass, that incinerated, gasified or liquefied, can help to generate enough energy to feed our growing economies, fuel our cars, light our cities and keep the gears of industry churning.

Due to the incessant growth of the world's fuel demand and Brazil's massive and varied biomass production, this work focused on an previously studied biomass that showed promise but was for whatever reason ultimately discarded as a carburant fuel source. The need to expand on the industrial possibilities of utilizing the cassava root as an input for a modern biorefinary and advance the cause of renewable fuel sources in the tropics is its reason to be.

This paper aimed to evaluate the technical requirements of mass,energy and equipment in order to create a mixed cassava mill that produces both ethanol and starch from the cassava root much like a modern sugar cane mill produces both ethanol and sugar. In order to properly create a parallel between modern Brazilian sugar cane mills and the proposed cassava mill, a complete characterization of the cassava plant residue as possible solid fuel source for the industrial process was made. Also, as the mill would be considered a complete and mid scale biorefinery, an estimate was calculated for the probable electric energy by-product that would in turn be sold to the national market.

2. METHODOLOGY

2.1 Characterization of the cassava residue

In order to properly characterize the cassava plant and its agricultural residue as a possible fuel source for the boilers of the mill, the leaves and stems where ground using a Marconi MA 680 with a 20 mesh filter. The decision to study the residue as a whole was made due to the unrealistic possibility of the separation of the whole plant into its different sections in an actual production environment. The residue used was from a IAC 14 plant, as shown by Veiga *et al.* (2016) to have the best characteristics for the purpose of the biorefinery. An adequate combustion project develeped to generate energy through the burning of the cassava plant residues need to characterize both the chemical and physical properties of the biofuel that is to be utilized. This contributes to the information necessary to properly handle both solid and gaseous residues derived from combustion, while also enabling to properly dimension the equipment necessary for the task at hand Joseé and Bork (2011). Most analysis deemed necessary within the studied literature include:

- Proximate and Ultimate Analysis, including both Chlorine and Sulphur

- Gross and Net Calorific Value for the Fuel

- Ash Fusion

- Thermogravimetric Analysis

- Particle-Size Distribution

2.2 Inside the cassava mill: Industrial Process

The elaboration of a complete mass and energy balance for a cassava mill that does not exist as a whole was only made possible through the gathering of information from various sources, that allowed the junction of the different sectors of the biorefinary into one complete mass and energy flow map. Informations gathered by Camacho (2009), Leonel and Cereda (1999), Veiga (2012), de Camargo *et al.* (1990) and Olsen (1995) allowed for the complete mapping of the innings and outings of the cassava ethanol production while citetCereda1994 1996and citetLebourg1996 allowed for the mass flows of the starch sector of the biorefinary. All equipments and their nominal electrical consumptions, where gathered from the EBS equipment factory. Figure 1, shows the conceptual plant map, minimized as it is for the purpose of this extended abstract.
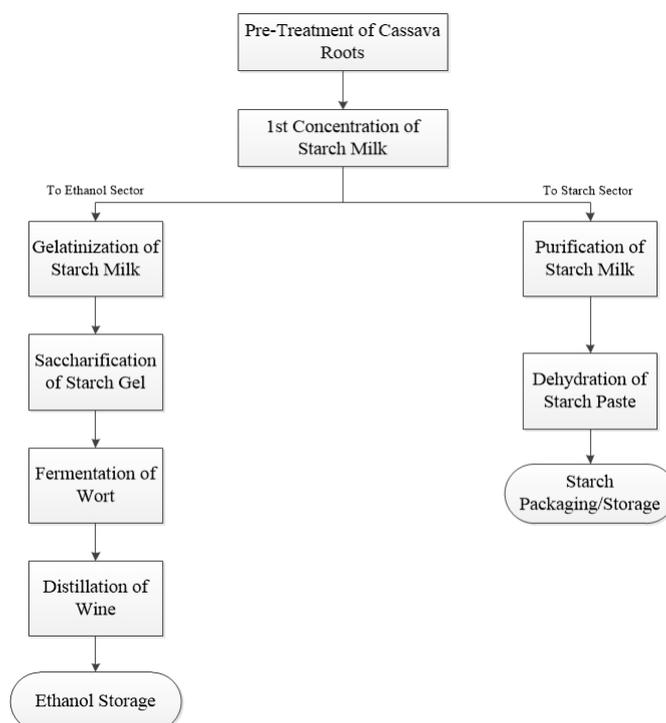

Figure 1. Processes structure of the biorefinary

The mass and energy flows where calculated for the processing of 1 ton of fresh cassava root. However, it is necessary to state that in order to reasonably utilize some of the components, especially of the co-generation plant, the entire biorefinery must have the same processing capacity of a medium scale plant so as to justify the cost of certain components.

2.3 Energy and mass: inside the cassava mill

The elaboration of a complete mass and energy balance for a cassava mill that does not exist as a whole was only made possible through the gathering of information from various sources, that allowed the junction of the different sectors of the biorefinary into one complete mass and energy flow map. Informations gathered by Camacho (2009), **?**, Veiga (2012), de Camargo *et al.* (1990) and Olsen (1995) allowed for the complete mapping of the innings and outings of the cassava ethanol production while citetCereda1994 1996and citetLebourg1996 allowed for the mass flows of the starch sector of the biorefinary. All equipments and their nominal electrical consumptions, where gathered from the EBS equipment factory. Figures 6, 7 and 8 show the complete flow map, built from the gathered information. The mass and energy flows where calculated for the processing of 1 ton of fresh cassava root. However, it is necessary to state that in order to reasonably utilize some of the components, especially of the co-generation plant, the entire biorefinery must have the same processing capacity of a medium scale plant so as to justify the cost of certain components.

2.4 Available fuel and energy: co-generation of the biorefinary

According to Veiga, the IAC 14 cassava variety presents at harvest 12 months after initial planting a medium production of 30.12 T/ha of roots (w.b.) and a production of 451 kg of field residue per ton of fresh root at 30% humidity. Totalling

an average residue production of 13.58 T/ha. This residue is a mixture of the leaves, superior branches and stems. Approximately 20% of the stems are collected and used in order to replant the crop for the next harvest.

In order to generate the energy, the biorefinary must have a co-generation sector that would follow the same schematics as those shown in 3. The basic parameters for the turbo generator are the following:

- Intake steam temperature at 460 °C.

- Intake steam pressure at 45 bar(abs).

- Extraction at 5 bar(abs).

- Expansion from 5 bar to 2.5 bar(abs.).

- Turbine iso-entropic efficiency at 85%.

- Electric generator efficiency at 98%.

For the steam generator the basic parameters are:

- Steam generator efficiency at 85%.

For the industrial processing sector the basic parameters are:

- Cassava root intake rate is, $\dot{m}_r = 150$ T/hr.

All of these parameters where considered as average for modern sugar-cane mills. The lower temperature was chosen due to the theoretical low ash fusion of the mixed cassava residues as stated by Veiga(2016) and the input pressure was determined for a vapor quality of 92% Carvalho (2015) as in figure 2 that would guarantee a safe operation for a turbine with out steam reheating.. Also, all pumps considered for the co-generation sector have an iso-entropic efficiency of 80%.
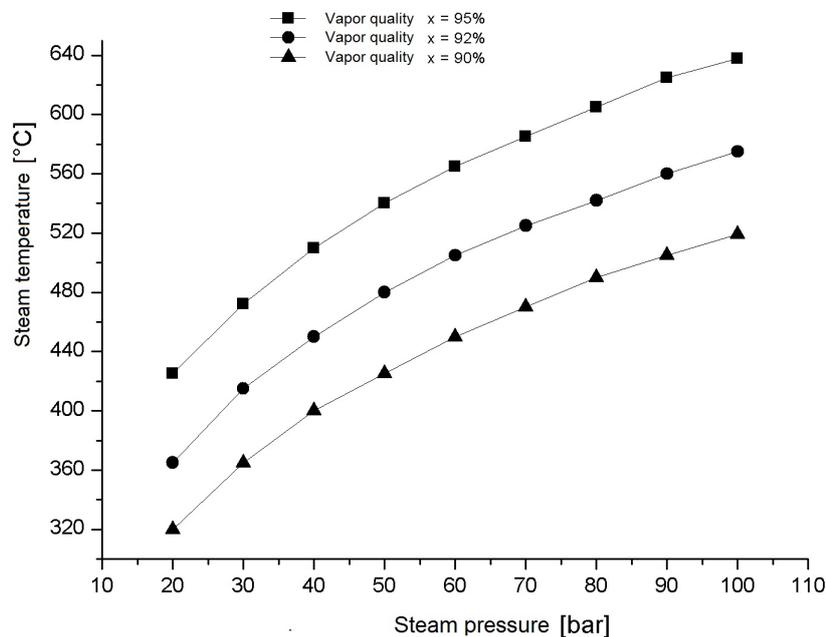

Figure 2. Vapor quality curves; Translated from **?**.

The processing input was chosen to be the base parameter for the calculation of all of the other mass flow rates in the other two sectors of the plant.The available fuel to the plant is based on the residue/roots ratios found for the IAC 14 Cassava plant multiplied by the root intake capacity.So, setting this parameter along with the technical specifications of the remaining industrial components, both of the agro-industrial sectors and the co-generation sector, a fuel addition rate or $\dot{m}_f$, for the steam generator can be calculated. Using the residues LHV and the generators efficiency.

Finally, the thermal energy necessary to process the roots can now be calculated using both the root intake rate and the steam conditions of each of the 3 thermal processes. This energy/mass balance will be necessary in order to extract the necessary amount of steam from the turbine. The electric energy will only vary according to the root intake rate and will subtract from the net electric generation of the bio-refinary.

Both the jet cooker and distillation column consume steam at 127.5 ° C and 2.5 bar(abs). However, the jet cooker injects steam directly into the starch milk flow while the distillation is done through indirect heating. In any case, the steam intake for the jet cooker, $\dot{m}_{s2}$ in (kg/s) depends solely on the calculated flow of starch milk, $\dot{m}_{sm}$ in (kg/s) and the milk's specific heat which was calculated proportionally from both water and starch C_p's.
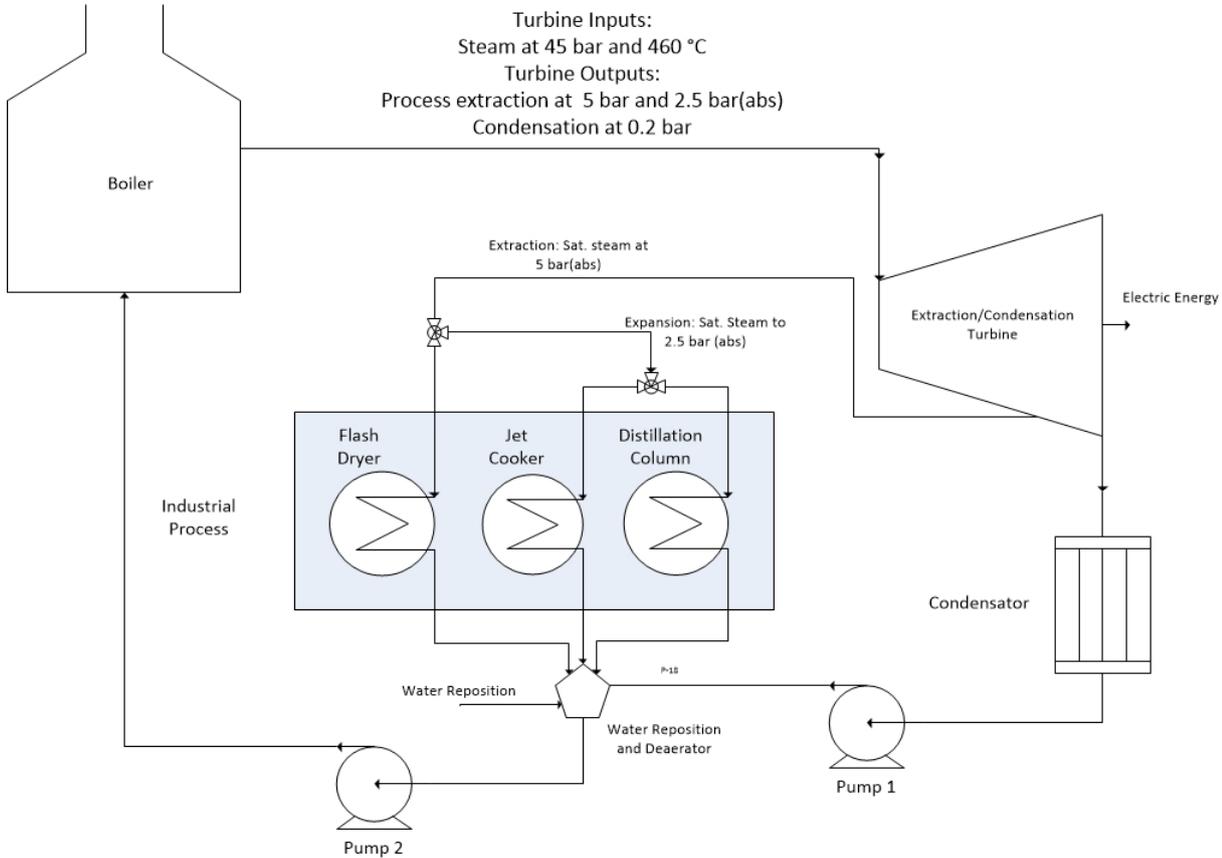
Turbine Inputs:
Steam at 45 bar and 460 °C
Turbine Outputs:
Process extraction at 5 bar and 2.5 bar(abs)
Condensation at 0.2 bar

Boiler

Extraction: Sat. steam at
5 bar(abs)

Electric Energy

Expansion: Sat. Steam to
2.5 bar (abs)

Extraction/Condensation
Turbine

Flash
Dryer

Jet
Cooker

Distillation
Column

Industrial
Process

Condensator

Water Reposition

P-18

Water Reposition
and Deaerator

Pump 1

Pump 2

Figure 3. Cogeneration scheme

2.4.1 Pre-treatment of roots

The pre-treatment of the roots is a stage in the industrial process is one that is shared by both the ethanol and the starch sectors of the plant and utilizes about a quarter of the total electric energy required by the plant at a 50/50 production rate (50% of starch milk is transformed into ethanol and the other 50% to starch).
In table **??**, the main components of the pre-treatment stage are listed.

2.4.2 Starch hydrolysis and saccharification

Turning starch into fermentable sugars is a section of the ethanol sector that requires a minuscule part of the total electric consumption of the biorefinery. The main components of this section are listed in table **??** which also includes the jet cooker, that only consumes thermal energy. Figure 4, demonstrates the mass flows within the jet cooker.

Steam Flow
(kg/s)

Cooked Milk Flow
(kg/s)

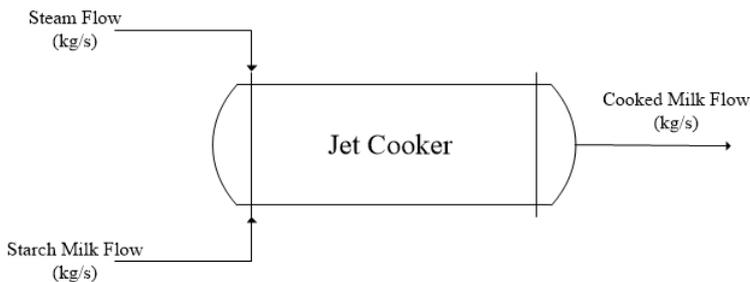Jet Cooker

Starch Milk Flow
(kg/s)

Figure 4. Flow diagram for the Jet Cooker.

The complete equation that calculates the steam flow rate for the jet cooker and subsequently the thermal energy required

by the process is as follows:

$$\dot{m}_{s1} = \frac{\dot{m}_{milk} C_p \Delta T}{(h_2 - h_1)} \tag{1}$$

in which:

- $\dot{m}_{s1}$ is the stean flow of the jet cooker.

- $\dot{m}_{milk}$ is the milk flow rate through the jet cooker.

- C_p is the milk's specific heat in kJ/(kgK).

- Δ T is the change in the milk flow temperature in °C.

- $(h_2 - h_1)$ is the enthalpy difference between the exit and entry enthalpies of the steam.

Both the jet cooker and distillation column consume steam at 127.5 °C and 2.5 bar(abs). However, the jet cooker injects steam directly into the starch milk flow while the distillation is done through indirect heating. In any case, the steam intake for the jet cooker, $\dot{m}_{s1}$ in (kg/s) depends solely on the calculated flow of starch milk, $\dot{m}_{milk}$ in (kg/s) and the milk's specific heat which was calculated proportionally from both water and starch C_p's.
However, in order to complete the mass and energy balance of the biorefinery, other factors must be taken into account. The stoichiometric conversion factor of the starch hydrolysis and subsequent saccharification as well as recorded efficiencies were gathered from the literature and listed in table 1.

Table 1. Starch to glucose conversion factors

	Source	Factor	Unit
Stoichometric Conversion Factor	?	1.3071	$\frac{kg_{glucose}}{kg_{starch}}$
Efficiency of the Starch Hydrolysis	Leonel and Cereda (1999)	0.9	$\frac{kg_{produced}}{kg_{stoichiometric}}$

2.4.3 Fermentation and distillation of ethanol

The fermenting process of discontinuous batch fermentation is approximately 13.7% of the total electric energy requirements. Table ?? shows that this consumption is mainly due to the pumps that transport the wort and fermented wine in and out of the dorns respectfully.
After the wine is filtered, it needs to be pumped through the distillation column and both the hydrated ethanol (97.5 °GL) and vinasse that exit from the distillation process must be taken to their respective storage tanks. The basic components of the distillation sector are also listed in table ??, which also includes the column that only requires a source of thermal energy, as stated before, a flow of steam ($\dot{m}_{s3}$).
Calculating the steam flow required by a distillation column is a bit trickier. The steam flow varies accordingly to changes in the column's internal architecture, wine flows and it's composition. Since the design of a distillation column is somewhat out of place of this dissertation's scope, the steam flow rate for the distillation column, $\dot{m}_{s3}$ in (kg/s), was set at an industry average for mid-large scale ethanol refineries of 3.2 kg/L of ethanol and converted to kg/s ?.
Just like the hydrolysis sector, the fermentation and subsequent distillation of the ethanol needs to include a certain set of conversion factors that again were gathered from the corresponding literature. These are listed in table 2 and are necessary to fully implement the mass flows shown in figures 7 and 8.

Table 2. Ethanol conversion and distillation factors

	Source	Factor	Unit
Stoichiometric Fermentation Factor	de Camargo et al. (1990)	0.6471	$\frac{L_{ethanol}}{kg_{glucose}}$
Efficiency of the Fermentation	de Camargo et al. (1990)	0.891	$\frac{L_{produced}}{L_{stoichiometric}}$
Efficiency of the Distillation	de Camargo et al. (1990)	0.9663	$\frac{L_{produced}}{L_{stoichiometric}}$

2.4.4 Purification and drying of starch

Table **??** lists the main remaining components of the production of starch. Here as stated before, the starch milk is purified, concentrated and dried in order to produce a high quality industrial or food-grade starch.

Unlike the previous components that used heat in their processes, the negative pressure dryer also consumes a copious amount of electricity as it needs to circulate air within the dryer in order to decrease the moisture of the starch paste that enters to a final 12-13% humidity.

For the flash-dryer needed to dry the starch paste onto 12% humidity, the extraction steam is required to be at 150 °C, which is approximately 4.76 bar(abs) at saturation point. Knowing this and and knowing the specific heat of solid starch and the starch flow rate, $\dot{m}_p$ in (kg/s), the needed air flow, $\dot{m}_{a1}$ in (kg/s), can be found. Sequentially, the intake steam flow rate for the starch dryer, $\dot{m}_{s2}$ in (kg/s) that will heat the dry air that comes in contact with the starch can be calculated.

Thermally speaking,the calculation of the required steam is not as straight forward as the equation for the jet cooker. The many mass inputs and outputs can be seen in figure 5.
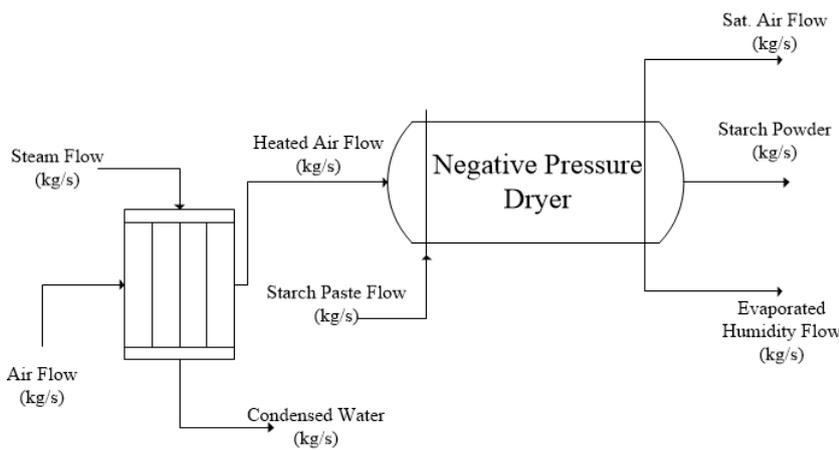

Figure 5. Flow diagram for the Starch Dryer.

Some assumptions about temperatures, air humidity and heat exchanger efficiencies will have to be made. Some of the considerations made were the following:

- The initial temperature of the starch paste is $T_{p1} = 30$ °C, while the final temperature is $T_{p2} = 40$ °C.

- The air that will be used as the drying fluid will enter the steam heat exchanger at $T_{a1} = 30$ °C at 62% humidity and exit at $T_{a2} = 140$ °C.

- The air exiting the dryer will be fully saturated at $T_{a3} = 90$ °C.

- Both the heat exchanger and the dryer were considered 100% efficiency, as no energy is lost to the environment.

The following mass and energy equations will characterize the amount of steam flow needed to transform the starch paste into a dry fine powder:

$$\dot{m}_e = (\dot{m}_{p1} - \dot{m}_{p2}) - (\dot{m}_{a1} - \dot{m}_{a2}) \tag{2}$$

in which:

- $\dot{m}_e$ is the mass flow evaporated water.

- $\dot{m}_{p1}$ is the mass flow of starch paste.

- $\dot{m}_{p2}$ is the mass flow of starch powder.

- $\dot{m}_{a1}$ is the mass flow humid air.

- $\dot{m}_{a2}$ is the mass flow saturated air.

Here two unknowns exist, the amount of incoming dry air and the amount of evaporated water that is not carried by the saturated air flow.

Next, the energy balance for the dryer will result in the second equation that will create the solvable equation system for both related variables.

$$\dot{Q}_{a2} + \dot{Q}_{p1} = \dot{Q}_{a3} + \dot{Q}_{p2} + \dot{Q}_{e} \tag{3}$$

in which:

- $\dot{Q}_{a2}$ is the amount of energy carried by the humid air at 140 °C.

- $\dot{Q}_{p1}$ is the amount of energy carried by the starch paste at 30 °C.

- $\dot{Q}_{a3}$ is the amount of energy removed by the saturated air at 90 °C.

- $\dot{Q}_{p2}$ is the amount of energy needed to heat the starch powder to 40 °C.

- $\dot{Q}_{e}$ is the amount of energy needed to evaporate the remaining amount of water.

Since the energy carried by the drying air and the energy expended to evaporate the starch pastes humidity involve directly their mass flows, with both of these equations it is possible to establish $\dot{m}_{a1}$. Finally in order to know the needed steam flow, an energy balance of the steam heat exchanger will be required.

$$\dot{m}_{s2} = \frac{(\dot{m}_a Cp_{a2} + \dot{m}_u Cp_{u2})T_{a2} - (\dot{m}_a Cp_{a1} + \dot{m}_u Cp_{u1})T_{a1}}{h_{fv}} \tag{4}$$

in which:

- $\dot{m}_{ss}$ is the mass flow of steam in the heat exchanger.

- $\dot{m}_a$ is the mass flow of dry air.

- $\dot{m}_u$ is the mass flow of water vapor at 62% humidit.

- Cp_{a2} is the specific heat of air at 140 ∘ C.

- Cp_{a1} is the specific heat of air at 30 ∘ C.

- Cp_{u2} is the specific heat of water vapor at 140 ∘ C.

- Cp_{u1} is the specific heat of water vapor at 30 ∘ C.

- h_{fv} is the evaporation enthalpy of steam at 150 ∘ C.

Finally, $\dot{m}_s$ is known.

3. PRELIMINARY RESULTS

The preliminary results are the creation of the mass and energy flow diagrams of the biorefinary. Figures 6, 7 and 8, contain the need information in order to properly study the energy expenditures of the industrial processing of either starch or ethanol for the cassava biorefinary.
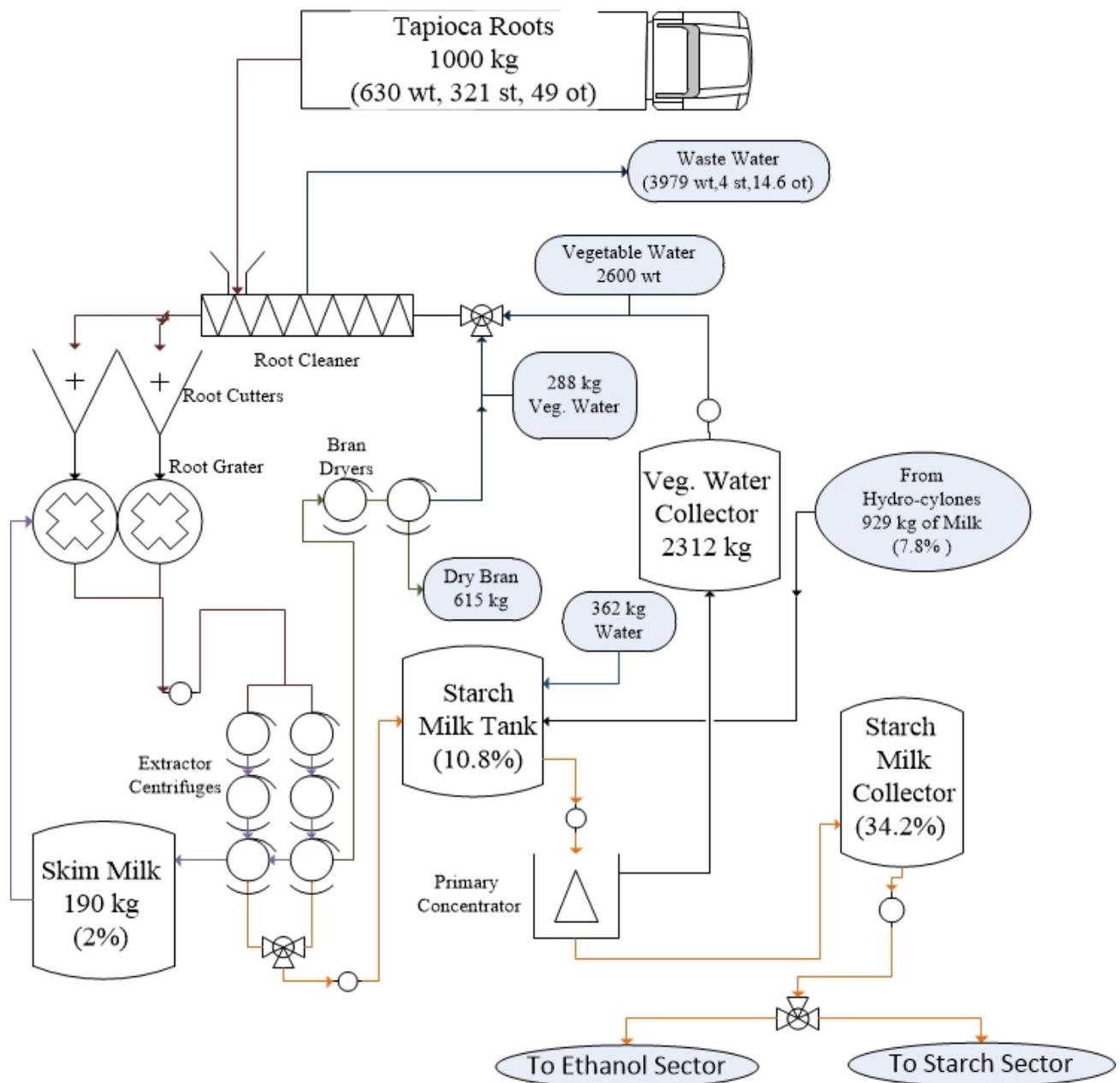
Figure 6. Pre-treatment of roots: cleaning ,grating and concentration of milk
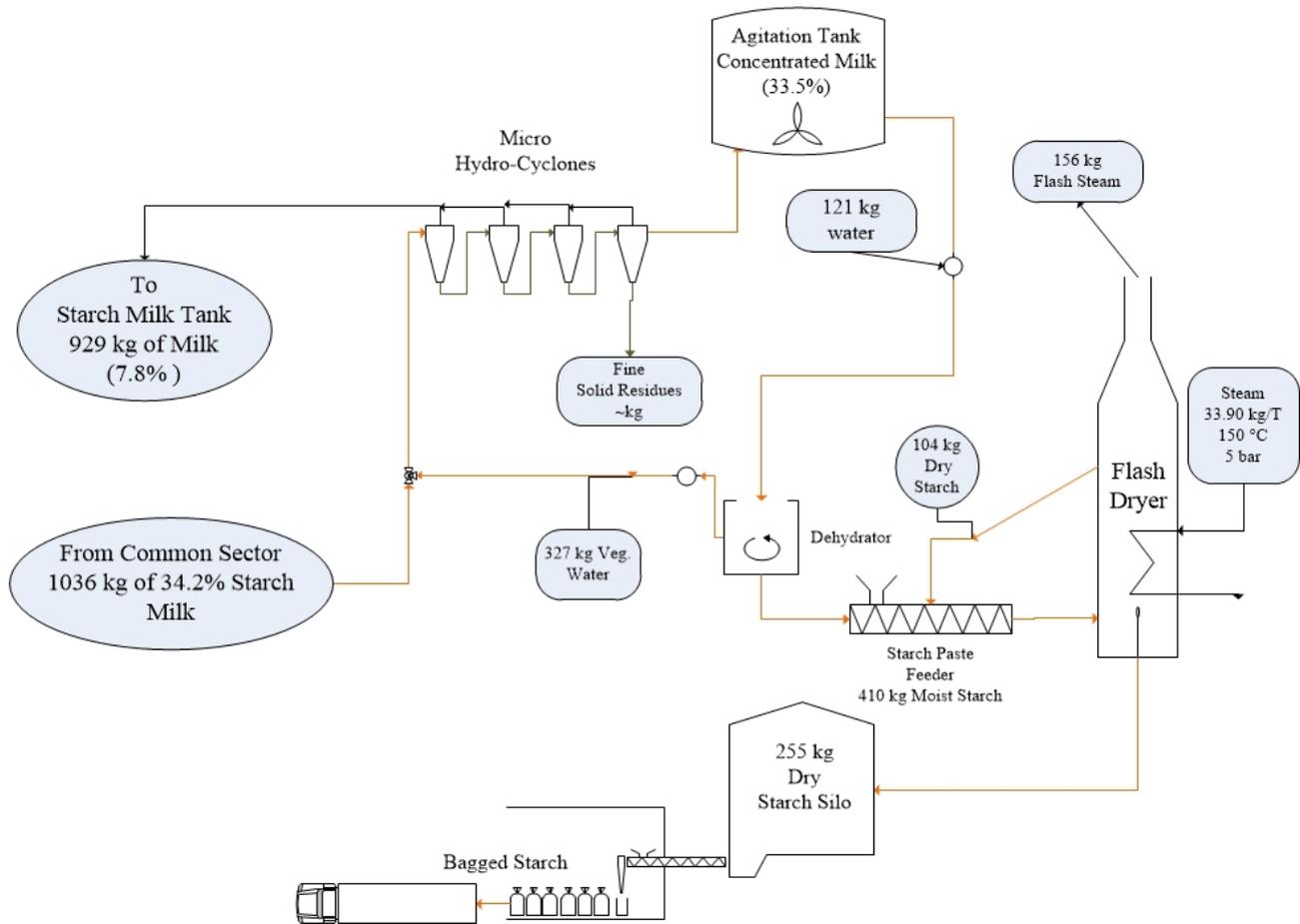
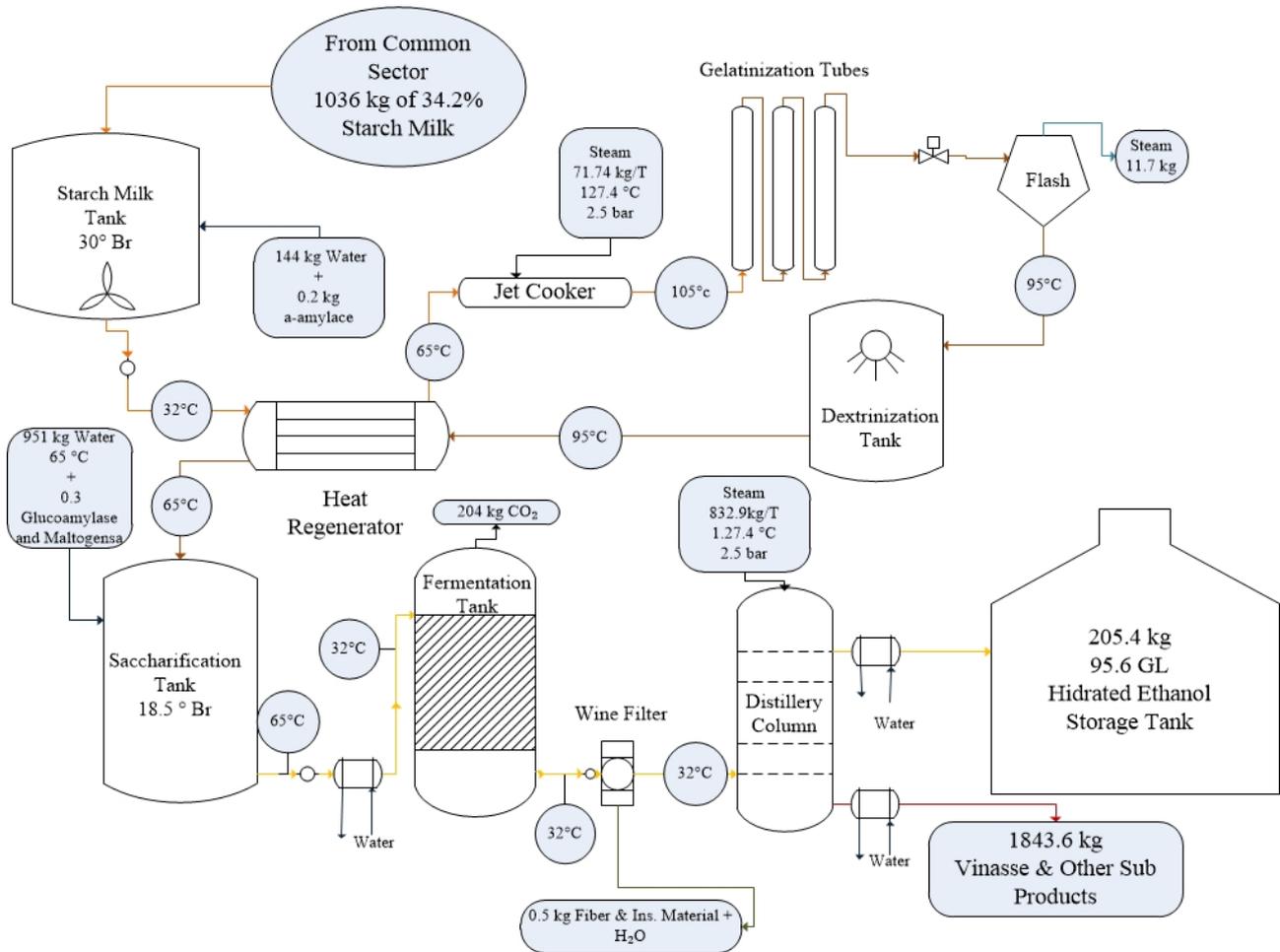Figure 7. Starch production sector of cassava mill

Figure 8. Ethanol production sector of cassava mill

4. CONCLUSIONS AND ADDITIONS TO FINAL PAPER

The mass and energy flow diagrams present a lower thermal energy input for the starch processing than for the ethanol sector, so accordingly the more starch is produced in detriment to the ethanol production, the more total electric energy can be generated for market sale.

With the completion of this paper the authors expects to achieve the following results:

- A more complete characterization of the above-ground segments of the cassava plant as a possible fuel source.

- A complete energy and mass flow for a cassava biorefinary that will produce ethanol and starch powder.

- An understanding of the optimal flux for either the ethanol or starch sectors of the industrial navel with regards to energy consumption and generation.

- An estimation of electric energy generation for third party buyers.

All of these results would further advance the needed data for a complete case study of cassava biorefinaries and their economic feasibility.

5. REFERENCES

Barbosa, C., Luís, A., Olivares, G., Silva, L., Electo, E. *et al.*, 2008. *Biomassa para energia*. L-0687. Unicamp.
Camacho, I.A.O., 2009. *Caracterização dos resíduos do processamento de mandioca para produção de bio-etanol e sua utilização na alimentação de aves*. Ph.D. thesis, UNESP.
Carvalho, D.J., 2015. "Geração de Bioeletricidade em Usina Sucroalcooleira Utilizando Bagaço, Palha de Cana e Sorgo Biomassa". p. 154.
Cereda, M.P., 1996. "Caracterização, usos e tratamentos de res{\'\i}duos da industrialização da mandioca". *Botucatu: Centro de Ra{\'\i}zes Tropicais*.

de Camargo, C.A., Ushima, A.H., Ribeiro, A.M.d.M., Souza, M.E.d.P. and dos Santos, N.F., 1990. "Conservação de energia na indústria do açúcar e do álcool". *São Paulo: Instituto de Pesquisas Tecnológicas*.

José, H.J. and Bork, J.A., 2011. "Caracterização de resíduos". In *Mini Curso conversão de resíduos em energia*. III Escola de Combustão, Salvador.

Leonel, M. and Cereda, M.P., 1999. "Melhoria do rendimento de hidrólise enzimática para produçao de etanol a partir de farelo de mandioca= Improvement of the yield in the enzymatic hydrolysis of fibrous cassava waste for the production of ethanol." *Brazilian Journal of Food Technology (Brasil).*, Vol. 1, No. 2, pp. 111–118.

Olsen, H., 1995. "Handbook of Starch Hydrolysis Products aud their Derivatives". In *Handbook of Starch Hydrolysis Products aud their Derivatives*, Springer, Norwich, chapter 2, pp. 26–63. ISBN 9781461359029. doi:10.1007/978-1-4615-2159-4.

Veiga, J.P.S., Valle, T.L., Feltran, J.C. and Bizzo, W.A., 2016. "Characterization and productivity of cassava waste and its use as an energy source". *Renewable Energy*, Vol. 93, pp. 691–699. ISSN 18790682. doi: 10.1016/j.renene.2016.02.078.

Veiga, P.S., 2012. *Caracterização de resíduos de c olheita da mandioca (Manihot esculenta CRANTZ) e avaliação do potencial de co- geração de energia no processo de produção de etanol*. Ph.D. thesis, UNICAMP.

6. RESPONSIBILITY NOTICE

The following text, properly adapted to the number of authors, must be included in the last section of the paper:
The author(s) are the only responsible for the printed material included in this paper.