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THERMODYNAMIC ANALYSIS OF AN ORGANIC RANKINE CYCLE USING THE BURNING OF THE AÇAÍ SEED AS HEAT SOURCE

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Abstract. *In Amazonas State, one of the fruits most consumed by the population is the açaí, whose cultivation makes possible important economic activities for the region, involving traditional populations and local businesses. However, only the pulp of the fruit is commercially exploited, being their seeds dumped into landfills. Researches have shown that the seed of açaí has great energy potential, with a Lower Heating Value equal to 3705 kcal/kg, and can be compared to others biomass used as fuel in several types of industries. In this study, energy and exergy analyses of an Organic Rankine Cycle were performed from the burning of the açaí seed, using three working fluids: R-245fa, R-600 and R-600a. The highest results were achieved with the turbine inlet pressure equal to 1600 kPa, and the R-245fa presented the best results of the three fluids, being the values obtained for the thermal efficiency, exergetic efficiency and power generated in the turbine, equal to 12.07%, 49.82% and 5497 kW respectively. With the analysis of the exergy destruction in the equipment of the cycle, it was verified that the greater irreversibilities occur in the evaporator, due to the high operating temperatures.*

Keywords: *energy, organic Rankine cycle, açaí, biomass.*

1. INTRODUCTION

Due to the growth of developing countries like Brazil, Mexico, India among many others, and the continued progress of developed countries, electric energy consumption has been increasing exponentially over the years, becoming a priority issue for governments.

In many of these countries, electricity generation is still highly dependent on fossil fuels, which, as seen in recent decades, the emissions of gases resulting from the burning of these fuels to the environment, contribute to the increase of the greenhouse effect and affect drastically the quality of the air, in addition to being limited energy resources. With these concerns, there has been an increase in the number of researches, looking for alternative sources of renewable energy and new technologies, which could reduce dependence on these fuels.

Heat sources such as solar, geothermal, biomass and others have shown great potential for energy generation, however, these are considered low-grade temperature heat sources, making it difficult to use with conventional power generation systems, due to the low thermal efficiencies that are obtained in these temperature levels (Jolevski *et al.*, 2017).

Among the technologies that have emerged to make the best use of these renewable sources, the Organic Rankine Cycle (ORC), which differs from the conventional Rankine Cycle only in the working fluid employed, has become very popular in energy production processes, due to the fact that gives the possibility of using low temperature levels as a heat source of the cycle, enabling the production of energy at the local level (Carlão, 2010; Orozco *et al.*,2012).

Açaí is one of the Amazon fruits, which has been gaining more and more prominence in the Brazilian market due to its high nutritional values and its health benefits. The largest producers are located in the northern Brazilian states, with the states of Pará and Amazonas accounting for 92% of the national production (CONAB, 2014). In Amazonas, the municipalities responsible for the cultivation of açaí are located to the east of the state, region farther from the Amazonian capital that is the main industrial pole of the northern region of the country, thus enabling important economic activities for these municipalities, involving traditional populations and local companies.

Açaí pulp is the main way the fruit is marketed, being used in the manufacture of ice cream, juices, sweets etc. The product that is left over when the pulp is removed from the fruit is the seeds, which are not reused, and are dumped in landfills. However, researches have shown that these wastes have great potential for energy, either as solid biomass or through chemical processes, turning them into biofuels. Considering this, the objective of this work will be to perform the thermodynamic analysis of an ORC using açaí seed as heat source, in order to show a new form of reuse for these residues, and perhaps to collaborate with the development of these municipalities with a new way of obtaining electricity.

2. AÇAÍ AND ITS ENERGY POTENTIAL

The açaí tree (*Euterpe oleracea*) is a typical Amazonian palm tree it occurs spontaneously in the states of Pará, Amapá, Maranhão and eastern Amazonas, where it provides important economic activities, involving traditional populations and local companies. This is the species used for the production of traditional açaí wine, and also for the production of heart of palm, removed from the terminal portion of the stem (SUFRAMA, 2003).

The production of açaí pulp, beverage or wine is carried out in two market segments. The first segment is handcrafted handlers, these establishments are responsible for supplying the local market, generating food, employment and income for thousands of people. The second segment is that of the agro-industries, which have as consumer market, other States of the Federation, mainly of the Southeast Region and also other countries of North America and Europe (Carneiro et al., 2013).

The açaí tree presents two varieties well-known by the citizens of the interior, whose differentiation is made only by the coloration that the fruits present when ripe, the purple açaí and the white açaí (Gantuss, 2006). The fruits are globose, measuring from 1,1 to 1,5 cm in diameter. They have a single seed, wrapped in a fibrous tissue and covered with a thin, dry but slightly oily layer of pulp.

The northern region of the country concentrates most of the vegetal extractive production. The production of açaí fruit is concentrated in Pará, responsible for 54.9% of Brazilian production. Second, it follows the state of Amazonas, with 35.5%, and the municipality of Codajás, in the interior of the state, is one of the largest national producers.

The exploitation of açaí in the State of Amazonas is predominantly extractive. It occurs in areas of concentration of two species, according to the region. The cultivation of açaí for fruit production is now being the object of greater interest on the part of the rural producers, given the increase in demand caused by the opening of new markets in recent years, mainly in the southeastern part of the country (SUFRAMA, 2003).

Considering that the processing is carried out in urban areas, the tailings are generally treated as garbage, bringing disruption to the urban garbage collection. Due to the increasing demand for pulp of the açaí fruit, the installation of industries to meet this demand is currently an activity with expansion in the Region, generating income and improving the quality of life for riverside and urban populations. However, from the processing, only the pulp is obtained. The seed (endocarp and almond) is the main byproduct of the processing, corresponding to 85% of the fruit, Fig. 1, and is considered waste (Carneiro et al., 2013).

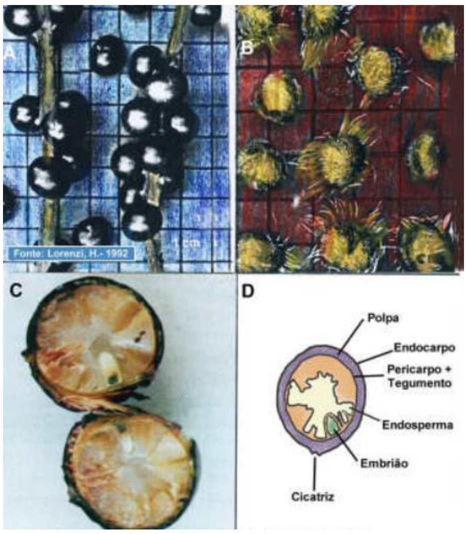

Figure 1: A) Fruits in nature; B) Seeds without pulp; C) Sectioned seed; D) Section layout (Padilha, 2005).

According to Gantuss (2006) the seed, after decomposition it is widely used as organic matter, being considered great fertilizer for the cultivation of vegetables and ornamental plants. However, it should be considered that the seeds of the açaí present a high energetic potential and that can be made available for the generation of energy of diverse forms, standing out the electric and the charcoal (Nagaishi, 2007).

Waste from the production of açaí, mainly for potteries, is marketed as biomass to feed boilers and ovens, replacing wood and reducing deforestation, thus being a source of clean energy (Silva, 2011). In order to evaluate the energy potential of a biomass it is necessary to know its Higher Heating Value (HHV), corresponding to the total heat released in the combustion.

The Higher Heating Value of açaí seed, according to Reis et al. (2002) and Rendeiro et al. (2008), is around 4500 kcal/kg (18828 kJ/kg), and its Lower Heating Value (LHV) according to Nagaishi (2007), is 3705 kcal/kg (15501,72 kJ/kg). It can then be compared to Eucalyptus (*Eucalyptus urograndis*), a wood very widespread throughout the country, commonly used as fuel for various types of industries and whose HHV is around 4680 kcal/kg (Carneiro et al., 2008). It is noted that the HHV values are relatively close, which characterizes the açaí seed as a viable and efficient energy input, besides being profitable.

3. ORGANIC RANKINE CYCLE

The Organic Rankine Cycle (ORC) is acknowledged as one of the most suitable technologies for valorizing low-grade heat into electricity or mechanical power. The working principle of an ORC is identical with that of a conventional steam Rankine engine: it constitutes a closed-loop thermodynamic cycle, into which a working fluid undergoes a series of processes (i.e. compression, evaporation, expansion and condensation) aiming to partially convert thermal power from a heat source into mechanical power. The distinction is related to the nature of the working fluid: instead of using water like in a conventional steam Rankine cycle, ORC systems employ organic compounds which are characterized by lower boiling points and higher molecular mass (Dickes et al., 2017). The challenge in designing the cycle lies in choosing the most appropriate organic working fluid and the configuration of the cycle itself (Carlão, 2010).

An ORC offers power generation from the renewable, waste heat and low- and medium-grade heat sources such as: geothermal, solar, biomass, and waste heat from the industry, primary movers, and thermal power plants (Javanshir; Sarunac, 2017). According to Silva (2010), the ORC operates between 60 and 200°C for low temperature sources and can reach 350°C in the case of medium temperature sources. This range of maximum cycle temperatures thus allows to work on different and varied types of regime and a considerably broader power range.

The increase in the number of researches in this cycle, involving several heat sources, can be explained in part by the type of modular construction. A single ORC system can be used, with few modifications, with several heat sources. Another relevant factor is that, unlike conventional cycles, the Organic Rankine Cycle allows the production of electricity at the local level (Carlão, 2010).

3.1 Working fluid determination

The Organic Rankine Cycle has as main characteristic the use of organic substances as working fluid, these being typically selected to meet the requirements of the particular application.

In selecting a working fluid for the Organic Rankine Cycle, it is expected that it maximizes the thermal efficiency of the cycle as well as the electrical power generated, and that it reduces the work required by the pump, taking into account the temperatures of hot and cold sources available. However, the choice of fluid indicated is not based solely on thermal and thermodynamic evaluations. Other issues are also evaluated, such as environmental risks, public health and safety issues and the economic aspects associated with each of the fluids, making the selection process more judicious and reasoned (Quoilin, 2007; Silva, 2010).

In this way, and with the purpose of defining and selecting the most suitable fluid for each type of application, the following issues are evaluated:

- Isentropic saturation vapor curve;
- Low freezing point, high stability temperature;
- High heat of vaporisation and density;
- Low environmental impact;
- Safety;
- Good availability and low cost;
- Acceptable pressures

According to Drescher and Brüggemann (2007), one of the widely used working fluids for biomass burning systems is Octamethyltrisiloxane (OMTS). However, to perform cycle analysis, was used the Engineering Equation Solver (EES), which library contains the thermodynamic properties of various types of fluids used in power and cooling systems, but does not contain OMTS properties. Therefore, this fluid will not be used in this analysis.

In the work done by Silva (2010), it was verified that the fluids that are part of the EES library, which would best apply to an ideal ORC, arriving at the conclusion that the fluids: R-245fa, R-600, R-600a, R-601, R-601a, are the ones that present the best performances. However, for this analysis, only the R-245fa, R-600, R-600a fluids were used, because the version used did not contain the properties of the other two fluids. Table 1 shows some properties of these three fluids.

Table 1: Properties of Selected Working fluids (Unisinos, 2017)

Fluid	T_{crit} (°C)	P_{crit} (kPa)	ODP	GWP	Flammability Limits (% of air volume)	
					L_{min}	L_{max}
R-245fa	154	3651	~0	1020	-	-
R-600	152	3796	~0	520	1,8	8,5
R-600a	134,7	3640	~0	490	1,8	8,4

4. THERMODYNAMIC ANALYSIS

The cycle that will be used for a thermodynamic analysis is shown in Fig. 2. As the ORC systems that use biomass are commonly operated in cogeneration systems, the addition of a regenerator increases the thermal efficiency due to heat transferred internally does not require an external source to be supplied.

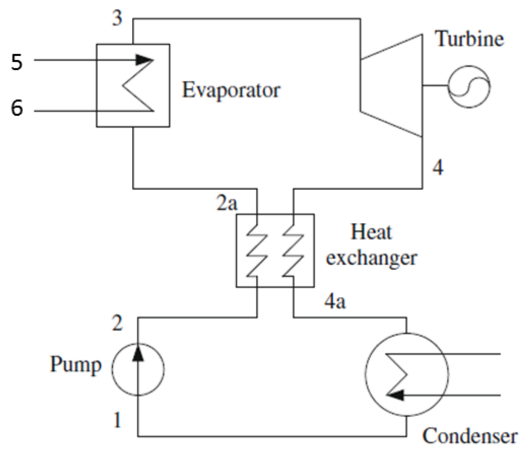

Figure 2: Schematic representation of a Rankine cycle with regenerator (Dai et al., 2009)

4.1 Energetic Analysis

The energy balance equations Eq. (1), and mass balance Eq. (2), applied to a device with steady-state flow will be:

$$(\dot{Q}_e - \dot{Q}_s) + (\dot{W}_e - \dot{W}_s) = \dot{m}_s h_s - \dot{m}_e h_e \quad (1)$$

$$\sum \dot{m}_s = \sum \dot{m}_e \quad (2)$$

Where:

- $\dot{Q}_e$ and $\dot{Q}_s$: are the amounts of heat being added and rejected from the control volume in kW;
- $\dot{W}_e$ and $\dot{W}_s$: are the potentials introduced and supplied by the control volume in kW;
- h_s and h_e : are the enthalpy values of the working fluid in the inlet and outlet state of the control volume in kJ/kg;
- $\dot{m}_s$ and $\dot{m}_e$: are the mass flow values of the working fluid at the inlet and outlet of the control volume in kg/s.

Performing the analysis for each device of the Rankine cycle, we have:

- Pump:

$$\dot{W}_P = \dot{m}(h_2 - h_1) \quad (3)$$

- Evaporator:

$$\dot{Q}_E = \dot{m}(h_3 - h_{2a}) \quad (4)$$

- Turbine:

$$\dot{W}_T = \dot{m}(h_3 - h_4) \quad (5)$$

- Condenser:

$$\dot{Q}_C = \dot{m}(h_{4a} - h_1) \quad (6)$$

- Regenerator:

$$h_{2a} + h_{4a} = h_2 + h_4 \quad (7)$$

The thermal efficiency of the Rankine cycle is determined by:

$$\eta = \frac{\dot{W}_{LIQ}}{\dot{Q}_E} \quad (8)$$

Where,

$$\dot{W}_{LIQ} = \dot{W}_T - \dot{W}_P \quad (9)$$

The real steam power cycle differs from the ideal Rankine cycle because of the irreversibilities in various components. The friction of the fluid and the loss of heat to the environment are two common sources of irreversibilities.

The irreversibilities that occur within the turbine and the pump are particularly important. A pump requires higher work consumption and a turbine produces less work because of the irreversibilities. Under ideal conditions, the flow through these devices is isentropic (Çengel, 2006). The deviation between the real and isentropic pumps and turbines can be calculated using the isentropic efficiencies defined as

- For the pump:

$$\eta_P = \frac{\dot{W}_s}{\dot{W}_r} = \frac{h_{2s} - h_1}{h_{2r} - h_1} \quad (10)$$

- For the turbine:

$$\eta_T = \frac{\dot{W}_r}{\dot{W}_s} = \frac{h_3 - h_{4r}}{h_3 - h_{4r}} \quad (11)$$

Where states 2r and 4r are the real output states of the pump and turbine, respectively, and 2s and 4s are the corresponding states for the isentropic case.

4.2 Exergetic Analysis

The ideal Rankine cycles are only internally irreversible and may involve irreversibilities external to the system, such as heat transfer with finite temperature difference. A Second Law analysis for these cycles reveals where the greatest irreversibilities occur and what their magnitudes are (Çengel, 2006).

The exergy is the maximum work or power that can be produced by a system or flow, when it goes through an entirely reversible process, and reaches the state of equilibrium with the environmental conditions. The thermomechanical or physical exergy is for a mass flow that crosses the boundary of the control volume given by equation:

$$\dot{X}^F = \dot{m}[(h - h_0) - T_0(s - s_0)] \quad (12)$$

Where the terms T_0, s and s_0, represent the ambient temperature and entropy values of the working fluid. When there is only one working fluid in a single concentration, chemical exergy is not required (Cavalcanti, 2016).

The destruction of exergy for a system with permanent regime flow can be expressed as a rate as

$$\dot{X}_D = T_0\left(\sum_s \dot{m}s + \frac{\dot{Q}_s}{T_s} - \sum_e \dot{m}s - \frac{\dot{Q}_e}{T_e}\right) \tag{13}$$

Where T_e and T_s are the boundary temperatures of the system where heat is transferred into and out of the system, respectively.

Using this equation, the analysis is performed for each device of the cycle

- Pump:

$$\dot{X}_{D,P} = T_0\dot{m}(s_2 - s_1) \tag{14}$$

- Evaporator:

$$\dot{X}_{D,E} = T_0\left[\dot{m}(s_3 - s_{2a}) - \frac{\dot{Q}_E}{T_e}\right] \tag{15}$$

- Turbine:

$$\dot{X}_{D,T} = T_0\dot{m}(s_4 - s_3) \tag{16}$$

- Condenser:

$$\dot{X}_{D,C} = T_0\left[\dot{m}(s_1 - s_{4a}) - \frac{\dot{Q}_C}{T_s}\right] \tag{17}$$

- Regenerator:

$$\dot{X}_{D,R} = T_0\dot{m}\left[(s_{2a} + s_{4a}) - (s_2 + s_4) + (1 - \eta_{reg})\left(\frac{h_4 - h_{4a}}{T_0}\right)\right] \tag{18}$$

The exergetic efficiency of the cycle is given by the following equation:

$$\eta_{exe} = \frac{\dot{W}_T}{(\dot{X}_5 - \dot{X}_6) + \dot{W}_P} \tag{19}$$

Where, $\dot{X}_5$ and $\dot{X}_6$ represent the exergies in points 5 and 6 of the cycle.

5. APPLICATION OF ORGANIC RANKINE CYCLE TO AÇAÍ SEED BURNING

In the year 2016, a total of 799.860 sacks of açaí fruit were collected, with each sack weighing 50 kg, the total of collected fruit was 39.993 tons. However, the açaí pulp corresponds to only 15% of the fruit. Extracting the percentage corresponding to pulp, the amount of açaí seed obtained is equal to 33.994,05 tons. With this value it is possible to obtain the value of the mass flow of the biomass. Considering an 8-hour day of operation and the year with 12 months of 30 days, the mass flow can be obtained from equation:

$$\dot{m}_c = \frac{C}{(t \cdot 3600 \cdot 360)} \tag{20}$$

Where the terms C and t are the values of the amount of açaí seed and the number of hours in operation, respectively. With the values considered the mass flow will be 3,278 kg/s.

The amount of heat supplied by the burning of the açaí seed to the cycle is obtained with the values of mass flow, Low Heating Value and evaporator efficiency, represented by the following equation

$$\dot{Q}_E = \dot{m}_c \cdot LHV \cdot \eta_E \tag{21}$$

The value of the evaporator efficiency was assumed equal to 0,85. With this, the amount of heat supplied by the burning of the açaí seed will be equal to 31.928,6 kW.

With the values of the mass flow and the amount of heat obtained by the burning of the açaí seed, together with the selected working fluids, the EES was used to perform the simulation of the ORC with regenerator.

The conditions of temperature and ambient pressure were considered to be equal to 30°C and 101,3kPa, respectively. At point 1, the working fluid is in the saturated liquid state, with a temperature of 40°C, due to the climatic conditions of the region, and with the pressure at this point equal to the saturation pressure of the fluid used.

With the isentropic efficiency of the pump equal (η_B) to 0,75 and the pressure P_2, which will be the variation parameter to evaluate the performance of the cycle and its components, the state of the fluid at point 2 can be determined. Point 2a, disregarding the head loss in the regenerator, will have the pressure equal to P_2, and through the energy balance in the regenerator, the value of T_{2a} is obtained.

The evaporator outlet temperature, which is the highest temperature of the ORC, was considered to be equal to 120°C, whose value is below the values of the critical temperatures of the evaluated fluids. The pressure at this point will be equal to the pressure P_2.

The condition of the fluid at the turbine outlet can be defined by assuming the isentropic efficiency of the turbine (η_T) equal to 0,75, and the pressures P_4, P_{4a} and P_1 as the same, disregarding the head loss in the regenerator and condenser. In the regenerator, there must be a temperature difference of the order of 5°C between the inlet temperature of the saturated liquid (cold side) T_2 and the steam outlet (hot side) T_{4a}, according to Dai, Wang and Gao (2009) being this value admitted.

The Dowtherm A fluid was chosen as the thermal fluid, which will transfer the heat resulting from the burning of the açaí seed to the cycle. This fluid presents good heat transfer properties, in addition to having its thermodynamic properties included in the EES library. According to Quoilin et al. (2013), the temperature of the thermal fluid should be between 100 and 300°C, so for point 5, the temperature of 200°C was chosen. For point 6, a difference of 10°C was established between the temperatures T_6 and T_{2a}, which according to Quoilin (2008), is a value given as a rule of good practice for refrigeration systems, taking into account thermodynamic and economic factors. The pressures P_5 and P_6 are the same, disregarding the head losses in the evaporator.

6. RESULTS AND DISCUSSIONS

Figure 3 shows the thermal efficiency curve of the cycle as a function of the pressure at the turbine inlet.

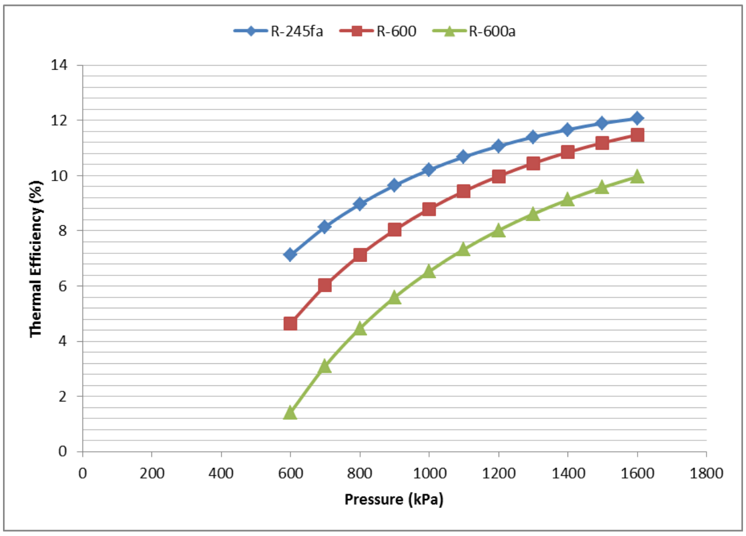

Figure 3: Thermal Efficiency of the ORC as a function of the pressure at the turbine inlet

The pressure at the turbine inlet was varied from 600 kPa to 1600 kPa, with the highest cycle performance obtained with the pressure of 1600 kPa, with the values of 12,07%, 11,48% and 9,96%, for the fluids R-245fa, R-600 and R-600a respectively. For the R-245fa fluid, there was a discontinuity of the thermal efficiency values of the cycle when overheated, and there is no physical explanation for these values, since there is continuity of specific enthalpy values in the superheated steam zone that can be verified in diagrams pressure-enthalpy of the fluid. The same situation was registered by Carlão (2010), where it was given as justification for this discontinuity, the fact that the values of the physical properties of R-245fa, for superheated steam, were incorrectly introduced in the software EES.

The values of the efficiencies obtained with the pressure of 1600 kPa are within the range established by Schuster et al. (2009) from 6 to 17% efficiency for ORC systems, since Liu, Shao and Li (2011) state that the maximum efficiency for an organic Rankine cycle is 16,6%. In the work done by Saleh et al. (2007), efficiency values equal to 13,07%, 13,04% and 12,43% were obtained for the fluids R-245fa, R-600 and R-600a, respectively, for an ORC using a pressure maximum of 20 bar (2000 kPa) and a condensation temperature of 30°C.

Table 2 shows the results obtained for the pressure of 1600 kPa for the three fluids used. The highest power generated in the turbine was obtained by the R-245fa, with a value of 5.497 kW.

Table 2: Results obtained for the pressure of 1600 kPa

Fluid	$\dot{m}\ (kg/s)$	$\dot{W}_T\ (kW)$	$\dot{W}_P\ (kW)$	$\dot{Q}_C\ (kW)$	η
R-245fa	203,1	5497	282,1	37987	12,07
R-600	107,3	5272	315	38245	11,48
R-600a	120,5	4628	324	38898	9,962

6.1 Exergetic Analysis

After the thermal analysis of the ORC, the exergy analysis was carried out, where the values of the exergies, the exergy destruction in each component, as well as the exergetic efficiency, were obtained for each of the three working fluids used.

Figure 4 shows the exergetic efficiency values according to the pressure variation at the turbine inlet.

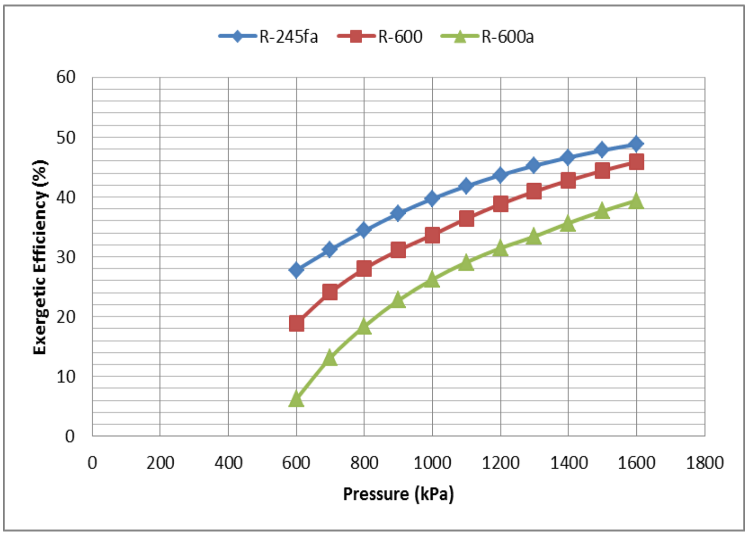

Figure 4: Exergetic Efficiency of the ORC as a function of the pressure at the entrance of the Turbine

The highest efficiencies were obtained with the pressure of 1600 kPa, being equal to 49,82%, 45,85% and 39,42%, for the fluids R-245fa, R-600 and R-600a, respectively.

The exergy destruction in each ORC equipment are shown in Tab. 3.

Table 3: Exergy Destruction Values in each ORC component

Equipment	Exergy Destruction (kW)		
	R-245fa	**R-600**	**R-600a**
Pump	68,4	76,45	78,66
Condenser	1211	1235	1254
Evaporator	7269	7548	8297
Regenerator	934,9	1256	1849
Turbine	1630	1527	1301

Figure 5 shows a comparative analysis of the exergy destruction in each component of the cycle.

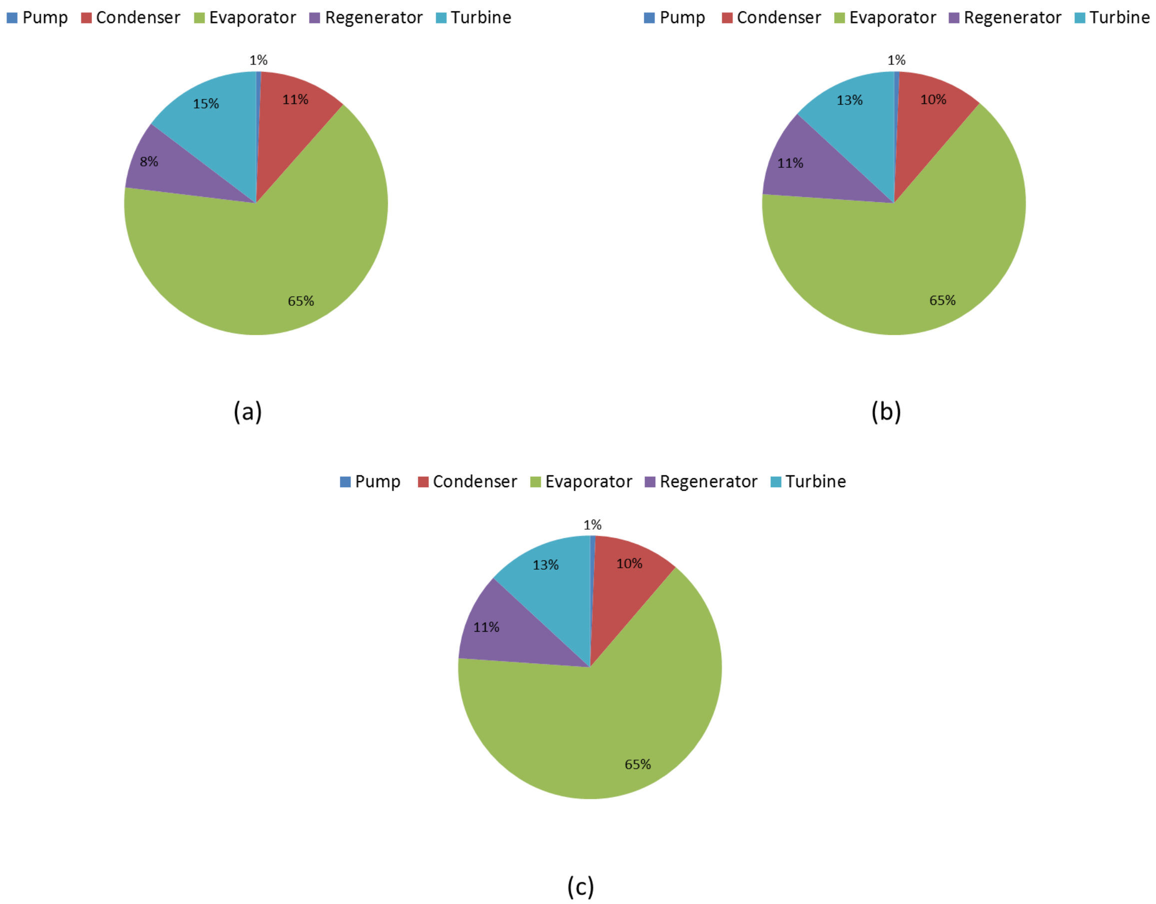

Figure 5: Percentage of each component in ORC exergy destruction. Fluids: (a) R-245fa; (b) R-600; (c) R-600a

Based on the analysis of the results, it is verified that the equipment, where much of the available exergy is wasted, are those that operate at a higher temperature and higher than the ambient temperature. In this way, the evaporator stands out from the other equipment, due to the high operating temperatures.

7. CONCLUSIONS

In this study the thermodynamic analysis of an Organic Rankine Cycle was performed, using the açaí seed as an energy source through its burning, demonstrating that its use can be compared to other biomass that are already used in various types of industry due to its energetic value. With this, the problems generated due to the large amount of residues coming from the production of açaí pulp can be solved by reusing these residues in energy generation.

From the values of the lower heating value of the açaí seed and the amount of açaí produced in the state of Amazonas, an energy potential of 31.928,6 kW was obtained for the burning of the açaí seed. From this potential, it can be obtained in an ORC with regenerator, using the fluids R-245fa, R-600 and R-600a, the values of thermal efficiencies equal to 12,07%, 11,48% and 9,96%, respectively, with the values of temperature and pressure at the turbine inlet equal to 120°C and 1600 kPa. It shows that the R-245fa has the best results among the three fluids used in this analysis. It can be obtained with this fluid, 5.497 kW of power in the turbine.

Applying the concepts of the second law of thermodynamics, exergetic analysis was performed in the ORC, where an exergetic efficiency of 49,82% was obtained for the R-245fa fluid, with the same input conditions in the turbine. With the analysis of the irreversibilities in the equipment, it was verified that the evaporator is the one most responsible for the irreversibilities generated in the cycle, which was already expected, due to its operating temperatures being higher than the ambient temperature.

The results obtained from this analysis confirm what the previous researches with açaí seeds affirmed, which is its great potential as a source of renewable energy, reducing the volume of waste in landfills and bringing development to the most distant regions of urban centers.

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