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Analysis of the Thermal Exploitation of the Vinasse from Sugarcane Ethanol Production through Different Configurations of an Organic Rankine Cycle

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The search for a reduction of the dependence on fossil fuels has made the use of low temperature thermal sources attractive to many companies that have chosen to install recovery systems to generate electricity. In Brazil, the main solution found for the disposal of vinasse, which is a liquid residue of the ethanol production process, is fertigation, but there are restrictions of dosages in the crop. The biodigestion of vinasse is also shown as an alternative, being a process of generating energy from the biogas produced. Despite presenting a wide range of benefits, the biogas production costs are not yet covered by the prices charged by the electric power concessionaires. The temperature of vinasse leaving the distillation is around 100 °C, and this residual heat can be used to produce electricity through an Organic Rankine Cycle (ORC). One of the major challenges in designing an ORC is the proper choice of working fluid for the operation. Although there are many options available for work fluids, there are also many restrictions in its selection. Thus, the main objective of this work is the study of the thermodynamic properties of the application of three different organic fluids (R22, R227ea and R124) in two configurations of the ORC for the utilization of residual heat from the vinasse resulting from the sugarcane ethanol production process, as well as the gain of power inserted to the power generation in a traditional Rankine Cycle used in sugarcane power plants. In general, the isentropic fluid R124 has an advantage among the other fluids for both of the configurations studied.

1. Introduction

Energy and development are strongly linked concepts, which is why it can be ensured that the progress of society depends on a broad and economical energy supply. However, it is now widely accepted that most energy-intensive industrial activities have a significant negative impact on the environment, especially those related to air pollution and global warming.

Within this context, the use of low temperature thermal sources has become attractive for many companies that have chosen to install recovery systems to take advantage of thermal waste from its activities for the generation of electricity. Other investments were earmarked for energy production from renewable resources such as solar and wind power, but only in recent years such projects have been viewed seriously.

An example of industry that can apply for this concept is the sugar and ethanol industry. Since 1970, there have been major investments in the Brazilian sugar and ethanol industry to boost ethanol production in the country. In 2004, Brazil was the largest producer and exporter of this fuel and according to the Union of Sugarcane Industry (UNICA, 2017) in 2015 the sugar and ethanol sector generated a GDP (Gross Domestic Produtc) of more than 113 billion Reais (33 billion Dollars), reaching 30 billion liters of ethanol from sugarcane.

One of the residues of the ethanol production is the vinasse. In Brazil, the main technical solution found for the disposal of vinasse is fertigation, but there are restrictions of dosages in the crop. The biodigestion of vinasse is also shown as an alternative, being more than a treatment, a process of generating energy from the biogas produced. The vinasse leaves the distillation column at a temperature of 100 °C, and this residual heat can be used to produce electricity through an Organic Rankine Cycle (ORC). The generation of electricity using this thermal residue can reduce the costs of treatment and disposal of the vinasse in the environment.

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The organic CRO cycle is similar to the conventional Rankine cycle which uses water as the working fluid, but uses a specific high specific organic compound as the working fluid. In the last two decades, the use and research in this technology have grown rapidly as an option in the recovery of heat from low and medium temperature sources such as solar energy, geothermal energy and waste heat from industrial processes. This technology has extended its applications to small cogeneration facilities using biomass as fuel, as it can be seen in this study.

One of the major challenges in designing an ORC is the proper choice of working fluid for the operation. This design decision has a great influence on the performance of thermal systems. Although there are many options available for work fluids (that can be classified as wet, isentropic and dry fluid), there are also many restrictions in its selection, related mainly to the thermodynamic properties, their safety and impacts on health and environment. Papadopoulos et al. (2010) recommend that the working fluids have high pressure and critical temperature to improve the thermodynamic performance of the working fluid, low specific heat to reduce the thermal load of the condenser, high latent heat of vaporization to promote recovery of the source heat and high conductivity to help the transfer of heat in the heat exchangers.

Chen et al. (2010) analyzed the influence of several criteria for the choice of work fluids, including latent heat, density, specific heat and critical point. In their results, it was observed that isentropic and dry fluids are better for the CRO cycle.

Li et al. (2015) performed simulations using the software Engineering Equation Solver (EES) software to determine the suitable working fluid for the simple organic Rankine cycle system in different temperature ranges. They discovered that the efficiency of the subcritical organic Rankine cycle system is the best when the parameters of the working fluid in the expander inlet are in the saturation state.

Also, depending on the type of organic fluid, there is a better configuration for the ORC, that can include a regenerator and reheating for a better efficiency. Thus, the main objective of this work is the study of the thermodynamic properties of the application of three different organic fluids (R22, R227ea and R124) in two configurations of the ORC for the utilization of residual heat from the vinasse resulting from the sugarcane ethanol production process, as well as the gain of power inserted to the power generation in a traditional Rankine Cycle used in sugarcane power plants.

2. Computational Procedure

The equations used in the modelling for the thermodynamic analysis were obtained by the adoption of simplifying hypotheses in Eq(1), Eq(2) and Eq(3), which represent the mass balance, energy balance and entropy balance respectively (Çengel and Boles, 2013).

$$\frac{dm_{CV}}{dt} = \sum \dot{m}_{in} - \sum \dot{m}_{out} \tag{1}$$

$$\frac{dE_{CV}}{dt} = \dot{Q}_{CV} - \dot{W}_{CV} + \sum \dot{m}_{in}\left(h+\frac{V^2}{2}+gz\right)_{in} - \sum \dot{m}_{out}\left(h+\frac{V^2}{2}+gz\right)_{out} \tag{2}$$

$$\frac{dS_{CV}}{dt} = \sum \dot{m}_{in}s_{in} - \sum \dot{m}_{out}s_{out} + \sum \frac{\dot{Q}_k}{T_k} + \dot{S}_{gen} \tag{3}$$

The thermal efficiency of the cycle was calculated using Eq(4).

$$\eta = \frac{\text{Net power output}}{\text{Heat input}} \tag{4}$$

Fluids were simulated in two different configurations: the basic ORC layout presented in Figure 1, and the regenerative cycle, presented in Figure 2. The simulations were made using the EES software, because it already has the thermodynamic properties of the various organic fluids to be studied. It was adopted as hypotheses that all processes occur in steady state, without variations of kinetic and potential energy, with heat transfer processes at constant pressure. The isentropic efficiency of the pump was considered as 0.85, and 0.90 for the turbine.

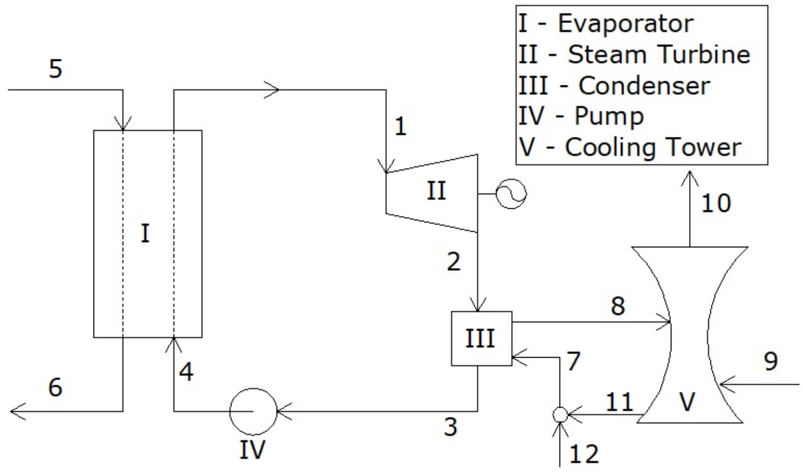

Figure 1: Layout of the basic configuration of the Organic Rankine Cycle for the ethanol production plant.

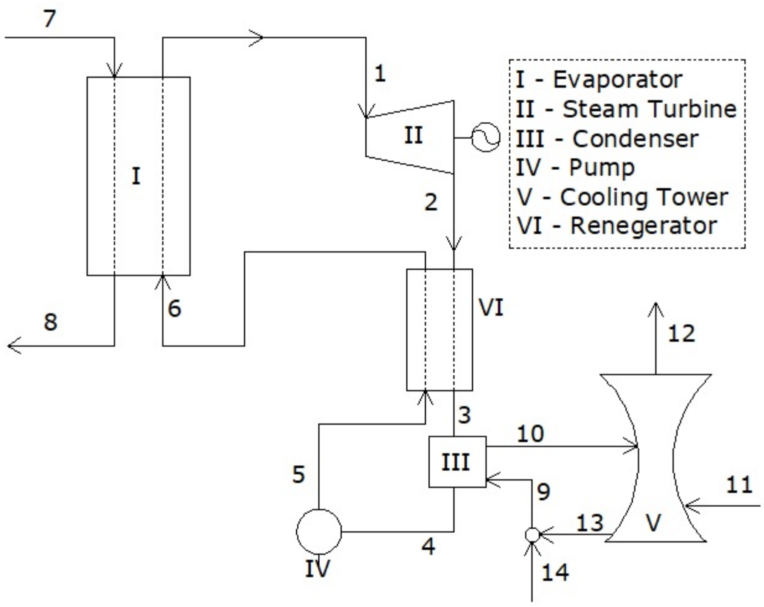

Figure 2: Layout of the regenerative cycle configuration of the Organic Rankine Cycle for the ethanol production plant.

The models developed used some input variables for both configurations. One of them is the mass flow of vinasse that operates as a heat supplier to the boiler (that corresponds to state 5 in Figure 1 and state 7 in Figure 2). This value was determined analytically from the data presented in Table 1.

Table 1: Parameters adopted for cycle simulation in both configurations (Dias et al., 2011).

Parameters	Values
Processed sugarcane	493 t/h
Ethanol production per ton of sugarcane (tc)	85 L/tc
Vinasse production	11 L/L of ethanol

Table 2 summarizes the initial parameters considered and calculated for all models in each state of the Figure 1 (basic cycle configuration), and Table 3 shows the parameters used for the states of Figure 2 (regenerative cycle configuration).

Table 2: Parameters used for the modelling of basic cycle configuration

State	Description	Considered Parameters	Calculated Parameters
1	Evaporator outlet	T_1 = 90ºC, P_1	h_1, s_1
2	Turbine outlet	$s_{2a}= s_1$, $P_2=P_3$	h_{2a}, x_2, h_2, s_2
3	Condenser outlet	T_3 = 35°C, x_3 = 0	h_3, s_3, P_3
4	Pump outlet	$P_4 = P_1$, $s_{4a} = s_3$	h_{4a}, h_4, s_4
5	Vinasse outlet of the process	T_5 = 100°C, x_5 = 0, m_5 = 127,7 kg/s	h_5, s_5
6	Reservoir input	T_6 = 25°C, x_6 = 0	h_6, s_6
7	Cooling water input at condenser	T_7 = 20°C, x_7 = 0	h_7, s_7
8	Cooling water outlet of condenser	$T_8 = T_7$ + 20°C, x_8 = 0	h_8, s_8
9	Damp air input at the cooling tower	T_9=20°C, P_9=100 kPa, φ_9=0,35	P_{g9}, P_{v9}, ω_9, h_{v9}, s_{v9}, s_{ar9}
10	Damp air outlet of the cooling tower	T_{10}=25°C, P_{10}=100 kPa, φ_{10}=0,85	P_{g10}, P_{v10}, ω_{10}, h_{v10}, s_{v10}, s_{ar10}
11	Cooling water input in the mixer	T_{11} = 20°C, x_{11} = 0	h_{11}, s_{11}
12	Water input in the mixer	T_{12} = 20°C, x_{12} = 0	h_{12}, s_{12}

Table 3: Parameters used for the modelling of regenerative cycle configuration

State	Description	Considered Parameters	Calculated Parameters
1	Evaporator outlet	T_1 = 90ºC, P_1	h_1, s_1
2	Turbine outlet	$s_{2a}= s_1$, P_2	h_{2a}, x_2, h_2, s_2
3	Regenerator outlet 1	$P_3 = P_2$, x_3 = 1	h_3, s_3
4	Condenser outlet	T_4 = 35°C, x_4 = 0	h_4, s_4
5	Pump outlet	$P_5 = P_6$, $s_{5a} = s_4$	h_5, s_5
6	Regenerator outlet 2	$P_6 = P_1$	h_6, s_6, x_6
7	Vinasse outlet of the process	T_7 = 100°C, x_7 = 0, m_7 = 127,7 kg/s	h_7, s_7
8	Reservoir input	T_8 = 25°C, x_8 = 0	h_8, s_8
9	Cooling water input at condenser	T_9 = 20°C, x_9 = 0	h_9, s_9
10	Cooling water outlet of condenser	$T_{10} = T_9$ + 20°C, x_{10} = 0	h_{10}, s_{10}
11	Damp air input at the cooling tower	T_{11}=20°C, P_{11}=100 kPa, φ_{11}=0,35	P_{g11}, P_{v11}, ω_{11}, h_{v11}, s_{v11}, s_{ar11}
12	Damp air outlet of the cooling tower	T_{12}=25°C, P_{12}=100 kPa, φ_{12}=0,85	P_{g12}, P_{v12}, ω_{12}, h_{v12}, s_{v12}, s_{ar12}
13	Cooling water input in the mixer	T_{13} = 20°C, x_{13} = 0	h_{13}, s_{13}
14	Water input in the mixer	T_{14} = 20°C, x_{14} = 0	h_{14}, s_{14}

3. Results and Discussions

By the difference between the T-s curves of different working fluids for the cycle, one can infer that each fluid will assign different operating characteristics to the same cycle. The working fluids can be classified according to their T-s curve as wet, dry and isentropic.

This study was made with a fluid representative of each class. R22 was selected from the wet fluids, R227ea from the dry fluids and R124 as isentropic fluid. The choice of those fluids only considered their thermodynamic characteristics. Among the parameters considered, P1 (pressure at the state 1) differs in all models, varying according to the fluid studied and the configuration of the cycle. Its value was determined based on the evaluation of the T-s curve, opting for values of pressure that the lines were around the temperature of the state 1 of the layout. Figures 3, 4 and 5 show the T-s curves plotted for each modelled fluid.

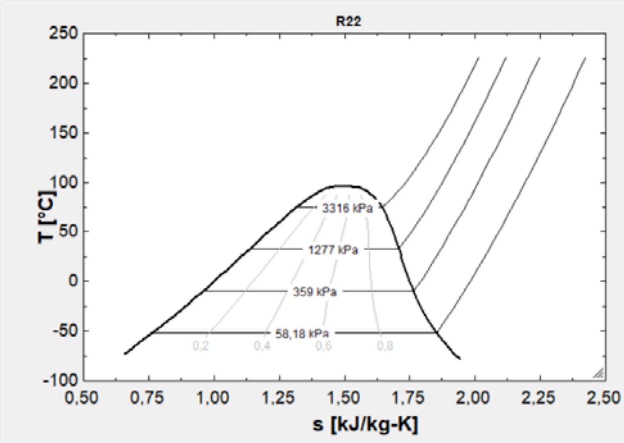

Figure 3: T-s curve of R22 (wet fluid)

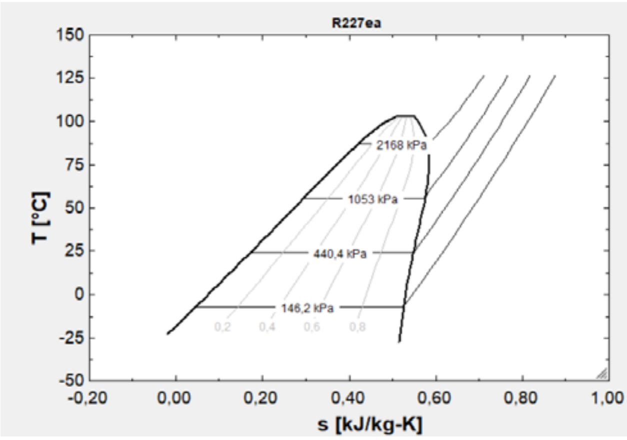

Figure 4: T-s curve of R227ea (dry fluid)

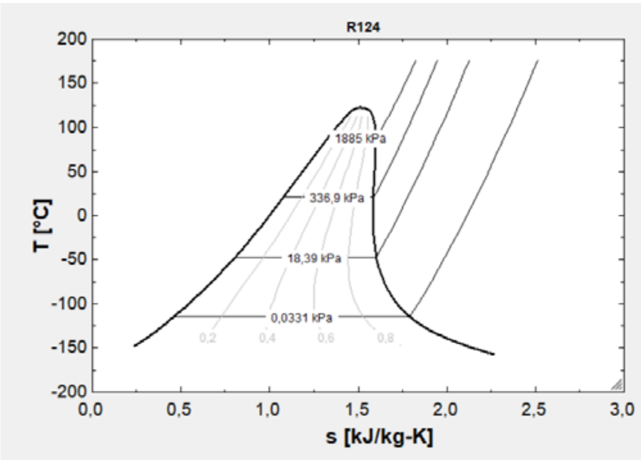

Figure 5: T-s curve of R124 (isentropic fluid)

Tables 4, 5 and 6 show the results of parameters calculated for each fluid, in both configurations simulated at EES software. The column of electricity surplus increase is considering the increase of electricity produced in the cycle when comparing to a traditional Rankine cycle, extracted from Dias et al. (2011).

Table 4: Parameters calculated at the simulations of R22 (wet fluid)

Configuration	Efficiency [%]	Produced power at the turbine [kW]	Consumed power in the pump [kW]	Electricity surplus increase [%]
Basic cycle	9.3	4201.0	468.2	12.1
Regenerative cycle	6.6	2864.0	210.0	8.6

Table 5: Parameters calculated at the simulations of R227ea (dry fluid)

Configuration	Efficiency [%]	Produced power at the turbine [kW]	Consumed power in the pump [kW]	Electricity surplus increase [%]
Basic cycle	9.2	4062.0	355.9	12.0
Regenerative cycle	9.3	3987.0	267.8	12.1

Table 6: Parameters calculated at the simulations of R124 (isentropic fluid)

Configuration	Efficiency [%]	Produced power at the turbine [kW]	Consumed power in the pump [kW]	Electricity surplus increase [%]
Basic cycle	10.7	4,618.0	300.7	14.0
Regenerative cycle	10.8	4,606.0	268.3	14.1

By the analysis of the results, it’s possible to notice that for the wet fluid, the basic configuration of ORC showed better performance than the regenerative cycle. On the other hand, for the dry and isentropic fluids, the regenerative cycle configuration showed a small advantage when comparing to the basic configuration.
In terms of cycle efficiency, the isentropic fluid R124 presented better results for both configurations. Nevertheless, all fluids presented a surplus of electricity produced (in kWh /tc), which, when combined to the conventional cogeneration systems, demonstrated in Dias et al. (2011), increase the total electricity produced, thus taking advantage of vinasse as a source of energy.

4. Conclusions

The parameters used to evaluate fluid performance are efficiency, power consumed at the pump, power produced at the turbine and electricity surplus increase for the traditional Rankine cycle. In general, the isentropic fluid R124 has an advantage among the other fluids for both of the configurations studied. When comparing the basic configuration to the regenerative configuration of ORC, the wet fluid R22 showed better results in the basic cycle, while the isentropic fluid R124 and the dry fluid R227ea showed better results in the regenerative cycle. For future studies, modifications can be made in the cycle to increase its efficiency. Such modifications can explore the characteristics of each fluid class and thus identify configurations that perform better. Also, ambiently and economic issues can be taken into account for future analysis.

Acknowledgments

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