24th ABCM International Congress of Mechanical Engineering
December 3-8, 2017, Curitiba, PR, Brazil

COBEM-2017-0517
THERMAL EXPLOITATION OF THE VINASSE THROUGH AN ORGANIC RANKINE CYCLE

Andressa Lodi
Universidade Federal do ABC, Centro de Engenharia, Modelagem e Ciências Sociais Aplicadas. Avenida dos Estados, 5001 - Santo André, SP, Brazil.
e-mail: andressa.brito@ufabc.edu.br

Mariana Rosa
Universidade Federal do ABC, Centro de Engenharia, Modelagem e Ciências Sociais Aplicadas. Avenida dos Estados, 5001 - Santo André, SP, Brazil.
e-mail: marianarosa.santos@yahoo.com.br

Marcelo Modesto
Universidade Federal do ABC, Centro de Engenharia, Modelagem e Ciências Sociais Aplicadas. Avenida dos Estados, 5001 - Santo André, SP, Brazil.
e-mail: marcelo.modesto@ufabc.edu.br

Abstract. *In Brazil, the main technical solution found for the disposal of vinasse is fertigation, but there are restrictions of dosages in the crop. The generation of electricity using this thermal residue can reduce the costs of treatment and disposal of the vinasse in the environment. Thus, the main objective of this work is the study of the thermodynamic properties of the application of three different organic fluids in an Organic Rankine Cycle (ORC) for the utilization of residual heat from the vinasse, as well as the gain of power inserted to the power generation in a traditional Rankine Cycle used in sugarcane power plants. The thermodynamic analysis was done in EES software with R290, R227ea and R124 fluids, and the results showed that all fluids have presented a surplus of electricity produced (in kWh / TC), which, when combined with the conventional cogeneration systems, increase the total electricity produced in a sugarcane power plant.*

Keywords: *Thermal Exploitation, Organic Rankine Cycle, Thermodynamic Analysis.*

1. INTRODUCTION

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 (Vieira et al., 2007) and according to the Union of Sugarcane Industry (UNICA) in 2015 the sugar and ethanol sector generated a GDP (Gross Domestic Produt) of more than 113 billion Reais (UNICA, 2017), reaching 30 billion liters of ethanol (Portal Brasil, 2017). Figure 1 shows a simplified diagram of the ethanol production process from sugarcane.

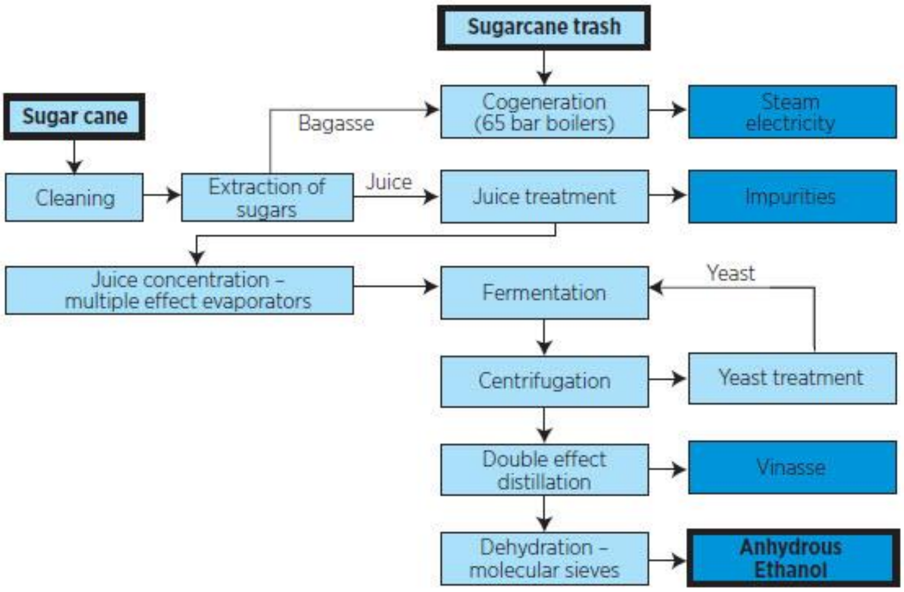

Figure 1. Ethanol Production Process (Cleanleap, 2017).

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. Despite presenting a wide range of benefits, the biogas production costs are not yet covered by the prices charged by the electric power concessionaires, being not competitive with the market value for medium and long term contracts.

The vinasse leaves the distillation column at a temperature of 100 ° C, and this residual heat can be harnessed 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.

When heat sources with low temperatures (< 200 ° C) are available, the ORC can be used to produce energy by operating with organic working fluids, different from traditional water steam. 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, there are also many restrictions in its selection, related mainly to the thermodynamic properties, their safety and impacts on health and environment.

Thus, the main objective of this work is the study of the thermodynamic properties of the application of three different organic fluids in an ORC for the utilization of residual heat from the vinasse, 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

2.1 Thermodynamic analysis of the Organic Rankine Cycle through EES software

The equations used in the modelling 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).

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

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

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

For the calculation of thermal efficiency of the cycle, the Eq. (4) was used, which represents a measure of performance.

$$\eta = \frac{Net\ power\ output}{Heat\ input} \quad (4)$$

An Organic Rankine Cycle has the same configuration as a traditional Rankine Cycle operating with steam; the main difference between them is exactly the workflow used. In Fig. 2, it can be observed the typical T-s curve of water and some organic fluids.

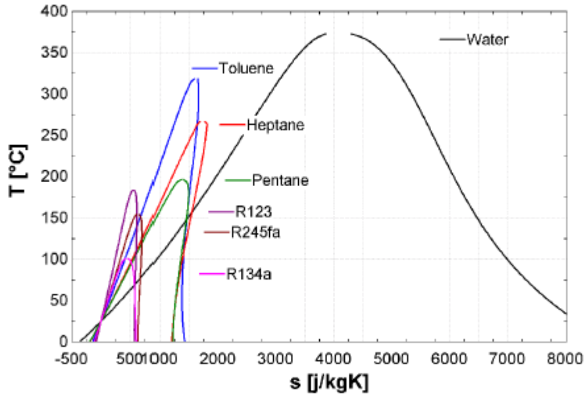

Figure 2. T-s curves of water and some organic fluids (Quoilin, 2011).

By the difference between the curves, 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. Thus, it is important to study those differences by working with one fluid of each type.

Fluids were simulated in the basic ORC layout presented in Fig. 3, 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, with no load losses and reversible. The isentropic efficiency of the pump was considered as 0.85, and 0.90 for the turbine.

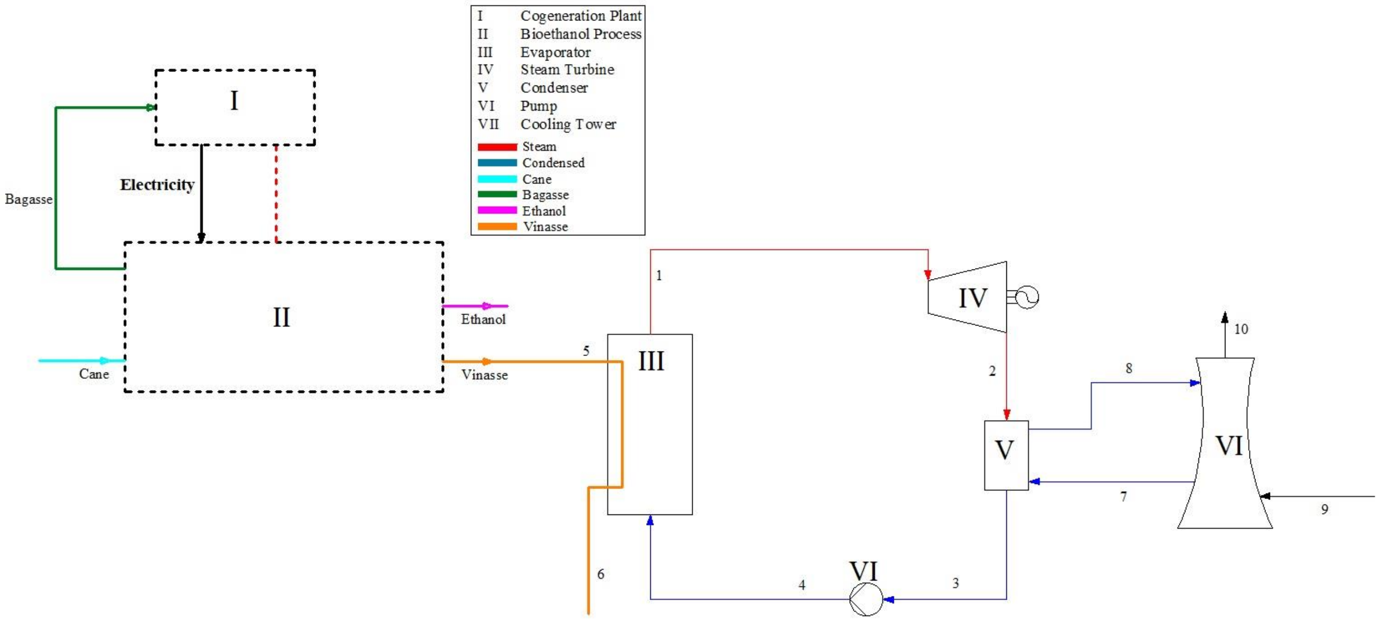

Figure 3. Basic layout of the Organic Rankine Cycle with the ethanol production plant.

For modeling, it is necessary to provide some variables, and one of them is the mass flow in states 5 and 6, that is the mass flow of vinasse that operates as a heat supplier to the boiler. This value was determined analytically from the data presented in Table 1 and considering $\rho_{vinasse} = \rho_{water}$.

Table 1. Parameters adopted for cycle simulation (Dias et al., 2011).

Parameters	Values
Processed sugarcane	493 ton/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 5.

Table 2. Parameters used in modelling.

State	Description	Considered Parameters	Calculated Parameters
1	Evaporator outlet	T_1 = 90°C, P_1	h_1, s_1
2	Turbine outlet	$s_2=s_1$, $P_2=P_3$	h_2, x_2, h_{2real}
3	Condenser outlet	T_3=34°C, $x_3=0$	h_3, s_3, P_3
4	Pump outlet	$P_4=P_1$, $s_4=s_3$	h_4, h_{4real}
5	Vinasse outlet of the process	T_5=100°C, $x_5=0$, m_5=126,04 Kg/s	h_5
6	Reservoir input	T_6=25°C, $x_6=0$	h_6
7	Cooling water input at the condenser	T_7=20°C, $x_7=0$	h_7, s_7
8	Cooling water outlet of the condenser	$T_8=T_7$+20°C, $x_8=0$	h_8, s_8
9	Damp air input at 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}, vol_9
10	Damp air outlet of 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}, vol_{10}

3. RESULTS AND DISCUSSION

The study was made with a fluid representative of each class. R290 was selected from the wet fluids, R227ea representative of the dry fluids and R124 as isentropic fluid.

Among the parameters considered, P1 (pressure at the state 1) differs in all models, varying according to the fluid studied. Its value was determined based on the evaluation of the T-s diagram, opting for values of pressure that the lines were around the temperature of the state 1 of the layout. Figure 4 (a, b and c) gathers the graphs plotted for each modelled fluid.

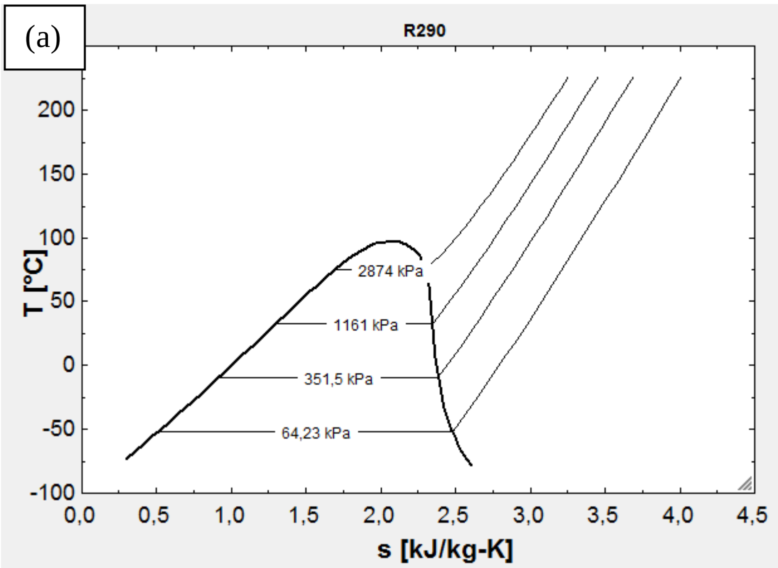

Figure 4(a). T-s diagram of R290.

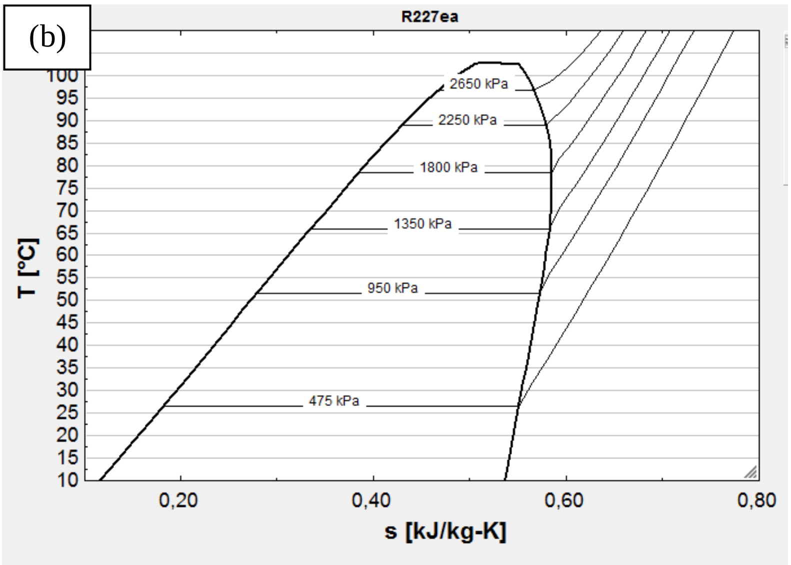

Figure 4(b). T-s diagram of R227ea.

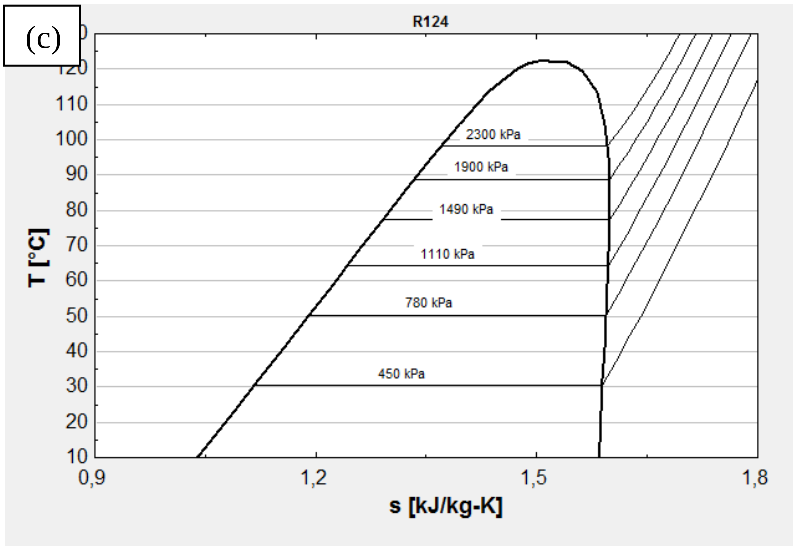

Figure 4(c). T-s diagram of R124.

At Table 3, the operation conditions of R290 at the ORC are presented, and Table 4 contains some parameters that present the performance of this fluid in the simulation.

Table 3. Operation conditions of R290.

R290 (wet fluid)						
State	**Description**	**Pressure [kPa]**	**Temperature [°C]**	**Enthalpy [kJ/kg]**	**Entropy [kJ/kg]**	**Quality (x)**
1	Evaporator outlet	3700	90	627,1	2,259	1
2	Turbine outlet	1189	34	587,2	2,273	0,931
3	Condenser outlet	1189	34	290,6	1,307	0
4	Pump outlet	3700	36,04	296,7	1,31	--

Table 4. Parameters calculated at the simulation of R290.

Efficiency [%]	Mass flow [kg/s]	Produced power at the turbine [kW]	Consumed power at the pump [kW]	Electricity surplus increase [%]
10,19	94,05	3573	578,6	9,692

At Table 5, the operation conditions of R227ea at the ORC are presented, and Table 6 contains some parameters that present the performance of this fluid in the simulation.

Table 5. Operation conditions of R227ea.

R227ea (dry fluid)						
State	**Description**	**Pressure [kPa]**	**Temperature [°C]**	**Enthalpy [kJ/kg]**	**Entropy [kJ/kg]**	**Quality (x)**
1	Evaporator outlet	2250	90	190,5	0,5845	1
2	Turbine outlet	591,6	43,81	176,1	0,5895	1
3	Condenser outlet	1438	34	60,61	0,2103	0
4	Pump outlet	2250	35,05	60,82	0,211	--

Table 6. Parameters calculated at the simulation of R227ea.

Efficiency [%]	Mass flow [kg/s]	Produced power at the turbine [kW]	Consumed power at the pump [kW]	Electricity surplus increase [%]
9,919	244	3498	355,6	10,17

Finally, at Table 7, the operation conditions of R124 at the ORC are presented, and Table 8 contains some parameters that present the performance of this fluid in the simulation.

Table 7. Operation conditions of R124.

R124 (isentropic fluid)						
State	**Description**	**Pressure [kPa]**	**Temperature [°C]**	**Enthalpy [kJ/kg]**	**Entropy [kJ/kg]**	**Quality (x)**
1	Evaporator outlet	1945	90	403,5	1,599	1
2	Turbine outlet	501,5	37,21	384,1	1,61	1
3	Condenser outlet	501,5	34	238,1	1,13	0
4	Pump outlet	1945	34,79	239,3	1,131	--

Table 8. Parameters calculated at the simulation of R124.

Efficiency [%]	Mass flow [kg/s]	Produced power at the turbine [kW]	Consumed power at the pump [kW]	Electricity surplus increase [%]
11,05	193,5	3763	247,8	11,38

Analyzing the results obtained, we can verify, in terms of cycle efficiency, a small advantage when using isentropic fluid R124. Nevertheless, all fluids presented a surplus of electricity produced (in kWh / TC), which, when combined with 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, in addition to reducing possible negative environmental impacts resulting from its final destination.

4. CONCLUSIONS

At first, the parameters used to evaluate fluid performance are efficiency, power consumed at the pump, power produced at the turbine and mass flow. Considering only these, isentropic fluid R124 has an advantage. The R290, despite being of the wet class, obtained a positive performance, being impaired by the power consumption in the pump. Although the R227ea presents lower efficiency and higher mass flow rate, its study is promising, because it presents a considerable internal temperature difference that can represent an opportunity of internal regeneration of the cycle to take advantage of this heat.

To date, only the most basic configuration of the Organic Rankine Cycle has been revised, but modifications can be made to increase its efficiency. Such modifications can explore the characteristics of each fluid class and thus identify configurations that perform better.

5. ACKNOWLEDGEMENTS

This work was supported by CAPES and Universidade Federal do ABC.

6. REFERENCES

ÇENGEL, Y. A.; BOLES, M. A. Termodinâmica. 7. ed. São Paulo: McGraw-Hill, 2013.

CLEANLEAP. Conventional Bioethanol production pathways. Available on: <http://cleanleap.com/4-bioethanol/41-conventional-bioethanol-production-pathways>. Acess in March 26, 2017.

DIAS, M.O.S. et al. Improving bioethanol production from sugarcane: evaluation of distillation, thermal integration and cogeneration systems. Energy, Amsterdam, v. 36, n. 6, p. 3691-3703, 2011.

PORTAL BRASIL. Economia e emprego. Available on: <http://www.brasil.gov.br/economia-e-emprego/2016/05/etanol-atingiu-producao-recorde-de-30-bilhoes-de-litros-em-2015>. Acess in: Feb. 12, 2017.

QUOILIN, S. Sustainable energy conversion through the use of organic rankine cycles for waste heat recovery and solar applications. 2011. 183 f. Tesis (Doctor in Ciências aplicadas) – Faculdade de Ciências Aplicadas, Universidade de Liège, Bélgica, 2011.

UNIÃO DA INDÚSTRIA DE CANA-DE-AÇÚCAR. Setor. Available on: <http://www.unica.com.br/noticia/705197392033158412/pib-do-setor-sucroenergetico-gerou-mais-de-r-por-cento24-113-bilhoes-em-2015/>. Acess in: Feb. 12, 2017.

VIEIRA, M. C. A.; LIMA, J. F.; BRAGA, N. M. Setor sucroalcooleiro brasileiro: Evolução e Perspectivas. São Paulo: Bndes, 2007. 40 p. Available on: <http://www.bndes.gov.br/SiteBNDES/export/sites/default/bndes_pt/Galerias/Arquivos/conhecimento/liv_perspectivas/07.pdf>. Acess in Feb. 12, 2017.

7. RESPONSIBILITY NOTICE

The authors are the only responsible for the printed material included in this paper.