25th ABCM International Congress of Mechanical Engineering
October 20-25, 2019, Uberlândia, MG, Brazil

COBEM-2019-1108
THERMOECONOMIC ANALYSIS OF THE RANKINE CYCLE WITH REGENERATION

Gabriel da Cruz Pereira Soares
Hugo Lima Moreira
João Lucas Lobato Soares
Universidade Federal Do Pará - Guamá, Belém - Pa, 66075-110
soares.gab@outlook.com
hugolimabr@yahoo.com.br
soaresjoao974@gmail.com

Abstract. *Due to the inexistence of inexhaustible sources of energy and perpetual cycle machines, as well as the constant attempts to reduce the emission of pollutants, several researches were started on the reuse of the various forms of energies present in a thermal cycle, in order to reduce losses and, consequently, to generate a more economic process. Nevertheless, this work intends to perform, through the Rankine Cycle and the software Engineering Equation Solver (EES®), a simulational analysis of the thermal and economic efficiency of the number of regenerators needed to more effectively reuse the heat generated by the boilers, prevent corrosion in the boilers and, thus, reduce the initial energy added to the system. In addition, after choosing the number of ideal regenerators for higher thermal efficiency, an analysis will also be made for the number of economically viable regenerators.*

Keywords: *Rankine, cycle, boilers, regenerators.*

1. INTRODUCTION

According to Çengel (2007), thermal power plants are responsible for the production of most of the world's electricity. Therefore, a small increase in yields translates into enormous global energy savings, with every possible effort being made to increase the efficiency of the plant's operating cycle. The basic concept used in increasing the thermal efficiency of the cycle is always the same: to increase the average temperature at which the heat is transferred to the working fluid in the boiler or to reduce the average temperature at which the heat from the working fluid to the condenser is discarded. That is, the average temperature of the fluid should be as high as possible during the addition of heat and as small as possible during the heat rejection. The main methods are overheating steam at higher temperatures, decreasing condenser pressure and increasing steam generator pressure.

Besides to the basic possibilities for obtaining a better performance, there are also special configurations that are created on the Rankine cycle with an improvement in its thermal efficiency. The most well-known are: reheating, when the steam expansion in the turbine is made in two stages with intermediate and regenerative reheating, when a part of the steam, after being partially expanded in the turbine, is extracted and used to preheat the water of food. Thus, for this work the EES (Engineering Equation Solver) program was used in order to find a higher thermal efficiency for the Rankine Cycle. So that regenerators were included to try to increase the cycle efficiency. Regenerators are machines that work as a mixer, it removes superheated steam from the turbine and directs it to the boiler, where a mixture of the vapor occurs with the water coming from the condenser, as shown in Fig.1. This causes the boiler need to provide less heat to evaporate the water and leave it to the temperature that will enter the turbine, consequently increasing the efficiency of the cycle. This yield can be further increased if more regenerators are included as it will further heat the water and further reduce the required heat supplied by the boiler, however, after a very high increase in the number of regenerators the yield stops increasing due to the fact that the amount of steam removed from the turbine before the expansion is completed is very high, causing it to generate much less work.

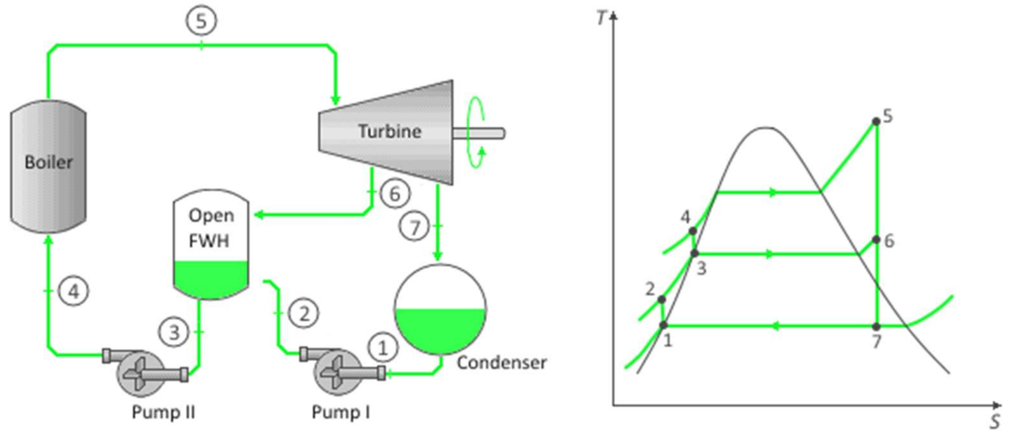

Figure 1. Rankine cycle.

An alternative to improve the above described condition is to use the process of regeneration. The purpose of regeneration is to increase the temperature of the working fluid before feeding the boiler. The regeneration process in thermoelectric plants is achieved through the extraction of steam from the extraction-condensation turbine. Extracted steam could produce more work by expanding further into the turbine rather than heating the feed water. The device where the feed water is heated by regeneration is called a regenerator or feed water heater (ÇENGEL and BOLES, 2011).

2. REGENERATORS

The T-s diagram of the Rankine cycle shown in Figure 1 indicates that heat is transferred to the working fluid during process 2-2 ', at a relatively low temperature. This condition reduces the average thermodynamic temperature in which the heat is added and therefore reduces the efficiency of the cycle.

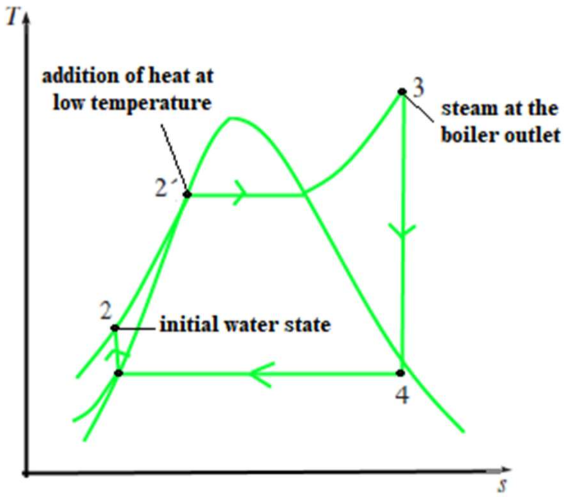

Figure 2. T-S diagram of Rankine cycle.

The regeneration not only improves the efficiency of the cycle, because it increases the average thermodynamic temperature in which the heat is added and also provides a convenient way to vent the feed water (eliminating the non-condable gases) to prevent corrosion in the boiler environment. It also helps to control the large volume of steam flow in the final stage of the turbine (due to the large specific volumes at low pressures) (CENGEL and BOLES, 2011).

3. EXPERIMENTAL PROCEDURE

In order to clearly describe what was done, the group will show the step-by-step procedure that was performed for the rankine cycle with only one regenerator, this was repeated with the other cycles, with more regenerators. First was set the initial data in the program EES, after that it was searched each point to obtain the results of specific volume, entalphy, entropy, title and temperature. How the table (1) below shows:

Table 1. thermodynamics data of cycle.

Enthalpy (Kj/Kg)	Pressure (kPa)	Entropy (KJ/Kg*k)	Temperature (°C)	Volume (L)
191.8	10	0.6493	45.82	0.001010
193.0	1200	0.6493	45.82	0.001138
798.7	1200	2.217	188.0	0.001138
814.4	15000	2.217	190.0	0.001129
3583	15000	6.68	600.0	0.010340
2860	1200	6.679	218.4	0.176700
2115	10	6.68	45.82	11.80000

To do the energetic analysis it is needed the energy data, the energy that comes in boiler and the one that comes out of the condenser, this way can be calculated the thermic efficiency, to calculate the energy entering the system it was used the difference between the enthalpy of point 5 and point 6 and for the energy leaving the cycle the group took the difference in enthalpy between point 7 and point 1, points that are shown in fig 1 That done, the following formula was used to calculate the thermal efficiency.

$$\eta_{th} = 1 - \frac{q_{out}}{q_{in}} \tag{1}$$

This procedure was done for all cases by varying the number of regenerators and the following results were obtained:

4. EXERGETIC ANALYSIS

According to Gomes (2011), this method showed that thermal efficiency always increases for even if the heat that comes in is less than if it there were no regenerates still the heat that comes out of the condenser is even less. However, this result it's not important for this work because the aim is to achieve an exergetic efficiency based in the exergy which was calculated according to the following form.

$$B = -T_0 * (S - S_0) + (h - h_0) \tag{2}$$

Where T_0,S_0, $h_0$is room temperature, entropy and enthalpy of Nevertheless, this result is unitary, to calculate the exergy of the system in the case it is needed to multiply this result for the mass flow, and to calculate the mass flow the turbine it was used the following form and from that this study obtained the mass flows in every point of the cycle:

$$\acute{m} = Pot/Q_e \tag{3}$$

The exergy of the pumps equal to the work produced by them, and the exergy of the fuel was consider to the unitary exergy is this value 832.650 Kj/kmol and was divided by the molar mass for obtained the exergy of the fuel. To the air the same process, considering the exergy 99,25.

To find the mass flow of fuel and air a stoichiometric analysis of combustion was made, where methane was considered as fuel and air as oxidant. A ratio of 1.5 air / fuel with this was obtained the fuel mass based in the total mass of the chemical equation multiplied by the ratio of the heat entrance in the boiler by the exergy of the fuel. Thereby can be calculated the total exergy the comes in the boiler and the total energy that comes out of the condenser.

5. EXERGOECONOMIC ANALYSIS

Now with all this data can be made the exergoeconomic balance that consists in assigning costs to the exergetic rates of an energy carrier and establish a monetary value to each one of the flows. The cost rate is linked to each exergy flow. Thus, to the exergetic flows of entrance and exit, of potency and associated to the heat transference, it was found:

$$\acute{C}_e = c_e * E_e = c_e * \acute{m}_e * e_e \tag{4}$$

$$\acute{C}_s = c_s * E_s = c_s * \acute{m}_s * e_s \tag{5}$$

$$\acute{C}_w = c_w * \acute{W} \tag{6}$$

$$\acute{C}_q = c_q * E_q = c_q * q[1 - \frac{T}{T_0}] \tag{7}$$

The terms c_e, c_s, $c_w$and $c_q$are the average costs per unit of exergy. Therefore, it will be found initially the monetary price of each component used in the system, to find this price the researches must know the acquisition rate of the components and maintenance (CAVALCANTI, 2009). The acquisition price was given in quick market research, thus obtaining the approximate prices.

Table 2. Price of equipaments

Equipment	Price ($)
Pumb	500
Turbine	960000
Condenser	100000
Boiler	400000
Regenerator	800

With the cost value of each equipment it was evaluated the leveled cost rate in which was considered factors of amortisation, fixed and variable costs with the operation and maintenance, capital recuperation factor (CRF).

$$\acute{Z}_i = \acute{Z}_i * CRF * \varphi \tag{8}$$

Where Z is the acquisition cost and φ is the maintenance factor and CRF is used in return on investment analysis and in amortisation of capital. It's value are portions of uniform value.

$$CRF = \frac{i*[\frac{(1+i)^{n_{year}}}{(1+i)^{n_{year}}_{-1}}]*1}{\eta_{year}*n_h*3600} \tag{9}$$

Where i is the annual interest rate n_year is the useful life in years and n_h is the number of hours of operation per year. Thus, considering inflation of 4% per year

Posteriorly, it's defined the categories: fuel, product and exergy destroyed in each subsystem. The fuel exergy (Ef) can be a current (fuel) or difference between the exergy coming in and the one that it's coming out, that losses energy by transference. The product's exergy (Ep) is the one intended, can be the exergy of a potency flow or the difference between the exergy of entrance and the exergy of exit that acquires exergy in the process. The destroyed exergy (Exd) is the difference of exergy between fuel and product.

To evaluate the performance of the equipments regarding exergy, it was used the energetic efficiency determinated by the relation between the exergy of the product and the fuel exergy. Where each component has an equation that relates exergy to its exergetic cost, the number of equations was equated with the number of variables to obtain the results.

6. RESULTS

With the procedure performed, initially were obtained the energy yields of each cycle with the different numbers of regenerators, thus this research obtained the following results:

Table 3. Relation of Thermal Efficiency

Number of Feedwater Heaters	Thermal Efficiency
1	46.31%
2	47.83%
3	48.81%
4	49.58%
5	50.29%
6	50.98%
7	51.67%
8	52.37%

The thermal efficiency always increases as shown in the table, but the amount of work produced is decreasing, which at some point ceases to be financially advantageous, thus obtaining the exergetic costs of each cycle flow with cycles of

1 to 4 regenerators and for this analysis a comparison will be made the cost exergetic the fuel the boiler with the work produces for turbine.

Table 4. Exergetic Cost of Fuel

Cycle	Mass flow of fuel (kg/s)	Exergy (Kj/s)	Exergetic cost of fuel ($/GJ)	Work (kJ/s)	Cost of fuel ($/h)
One regenerator	0.9958	51.629	0.1542	278.254	2.86
Two regenerators	0.8899	46.254	0.1542	236.477	2.57
Three regenerators	0.8662	45.022	0.1542	227.362	2.50
Four regenerators	0.8453	43.938	0.1542	219.319	2.44

Thus, when more regenerates are added the amount of saved fuel increases, which means significant savings, since boilers generally operate 24 hours a day, so in a month the amount saved using 4 regenerators compared to just 1 regenerator is $ 40.08 per month, but regenerator purchase and maintenance rate must be less than this saving for economically viable.

Table 5. Economic characteristics of the regenerator

Cycle	Flat Cost Rate of Regenerators($/h)	Flat Cost Rate of Pump ($/h)	Price of Regenerators ($)	Price of pump ($)	Economy ($/h)
One regenerator	0.00012	0.00007	800.0	500.0	0.00
Two regenerators	0.00024	0.00014	1600	1000	0.28
Three regenerators	0.00036	0.00021	2400	1500	0.35
Four regenerators	0.00048	0.00028	3200	2000	0.41

With this it can be observed that the boiler exergetic cost decreases more and more with the addition of more regenerators

7. CONCLUSION

Thus, it can be concluded that with the inclusion of more regenerators or exergetic cost of each equipment greatly decreases, we can observe that the boiler has a significant reduction due to the lower amount of fuel that must be inserted, but this reduction is not only in the boiler, since almost all components have this reduction, the pump as it needs to increase less pressure has this reduction, the condenser as it has less mass flow also has the reduction, the regenerators themselves with some more insertion, have a flow mass, so costs are reduced.

Therefore, the Rankine Cycle of the regenerators has it’s exergoeconomic efficiency increased with the addition of more regenerators and with the addition of until four regenerators the work loss is still compensated due to the gain that happened in the energy economy that would be placed in the boiler.

8. REFERENCES

Cavalcanti, E. J. C. Análise exergoeconômica e Exergoambiental. Blucher, 2009.

Çengel, Y. A., Boles, M. A. Thermodynamics. 6. ed. New York: McGraw-Hill, 2011.

Da Costa, H.V., Wander, P.R., Indrusiak, M.L.S.. Simulação De Ciclo Térmico Com Duas Caldeiras Em Paralelo: Combustão Em Grelha e em Leito Fluidizado. São Leopoldo, RS, 2009.

Díaz, Á. A. P. Avaliação termodinâmica da incorporação de sistemas de reaquecimento e regeneração nos sistemas de cogeração no setor sucroalcooleiro brasileiro, 2016.

Gomes, R. A. D. E. S. Modelagem Computacional De Caldeiras De Recuperação Térmica. Master's Thesis – UNICAMP, 2005.

9. RESPONSIBILITY NOTICE