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Exergetic Evaluation of a Rankine Cycle with Regeneration: Effect of Turbine Inlet Temperature and Source Temperature

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Abstract

The Rankine cycle is a thermodynamic cycle widely used in power plants, specifically in steam power plants, due to its great importance in the industry. It has also been studied in recent years in search of parameters that can optimize the cycle by reducing losses and thus increase efficiency, so that improvements have been made in the process such as overheating of steam at the turbine inlet, and even regeneration of water at the boiler inlet. In this work a process of optimization of a Rankine cycle was presented by complementing it with an open feed water heater which not only improves the efficiency of the cycle, but also provides a convenient means of de-aeration of the feed water to prevent corrosion in the boiler, in which it was carried out under the assumption of a stationary flow, and without significant changes in the kinetic and potential energy, that is, assuming an ideal process, all this with the aim of obtaining the highest thermal efficiency and the lowest exergetic losses in the cycle, carrying out several case studies with the assistance of Unisim with temperature variations at the turbine inlet and at the source to observe how this affects the exergetic efficiency and exergy destroyed in the turbine and it was concluded that this is reflected in the production of mechanical energy useful for creating electrical energy because a variation in these parameters could cause job losses in the turbine and decrease in the exergetic efficiency of the system which in turn would lead to a decrease in the network of the system.

Keywords: Regenerative Rankine cycle, thermal efficiency, exertion losses, pump efficiency, turbine efficiency.

INTRODUCTION

Considering the importance of the rational use of energy in thermal power plants and their impact on the environment, significant efforts have been made to improve the energy and energy efficiency of these types of power generation systems, since efficiency can be increased by making certain improvements that have the effect of minimizing losses [1],[2], in addition to providing significant benefits from the point of view of energy security [3], [4].

In many researches computer-aided simulation has been considered as a flexible, efficient and user-friendly tool that allows to simulate and optimize such thermodynamic processes as ProSimPlus® [5] [6], Aspen Plus ™ [7],[8],[9]. For example, the study of the thermodynamic performance of the organic Rankine cycle compared to the Kalina cycle made use of the Aspen HYSYS® software [10], obtaining that the waste heat comes from multiple sources divided into three streams such as straight, convex and concave waste heat, and that the Kalina cycle is most suitable [11],[12] and for the organic Rankine cycle, convex waste heat is preferred for a maximum heat source temperature of 180 °C in all cases [13],[14]. Among the proposed improvements is also the integration with renewable energy sources, where the impact of the replacement of thermal power plants by wind and photovoltaic energy could mitigate oscillations, causing a reduction in stability that allows a level of security of supply to be obtained [15].

The Rankine cycle is a thermodynamic cycle used in thermoelectric plants and aims to convert heat into work, through four fundamental components such as the pump, the boiler, the turbine and the condenser, of which the initial working potential is the heat supplied to the boiler. However, this process has been optimized by adding other components to the process to increase thermal efficiency, by increasing the average temperature at which heat is transferred to the working fluid in the boiler, or by decreasing the average temperature at which heat is rejected from the working fluid in the condenser, so that the average temperature of the fluid has been worked as high as possible during the addition of heat and as low as possible during heat rejection [16].

A commonly used method to increase the thermal efficiency of steam thermal power plants is regenerative preheating of the feed water or simply regeneration, which has been obtained by extracting steam from the turbine and preheating the boiler feed water with it, which has led to an increase in the average heat input temperature and, therefore, a higher overall Rankine cycle efficiency [17].

Therefore, the main contribution of the present work is to propose an analysis of the behavior of several case studies in a

Rankine thermodynamic cycle with regeneration by means of computer-aided simulation using Unisim, making it possible to evaluate the effect of the temperature variation at the turbine inlet on the efficiency of the effort, in addition to the exergy destroyed in the turbine.

METHODOLOGY

For the thermodynamic study of the process, the Unisim software was used, which is an interactive process engineering and simulation program, widely studied for the simulation of chemical plants and oil refineries, which uses fluid packages for the estimation of properties and vapor-liquid phase equilibrium, heat and material balances detailed below.

Fundamental equations.

For the modeling of the components of the cycle under the consideration of steady state flow, the energy and matter balances were applied, as shown in equation (1), taking into account that the changes in kinetic and potential energies are negligible.

$$\sum \dot{Q}_{in} + \sum \dot{W}_{in} + \dot{m}_{in}(h_{in}) = \sum \dot{Q}_{out} + \sum \dot{W}_{out} + \dot{m}_{out}(h_{out}) \quad (1)$$

The energy analysis of open feed water heaters is similar to that of mixing chambers, considering that the feed water heater is insulated and does not involve any working interaction, and that the kinetic and potential energies are negligible, so the resulting energy balance in the feed water heater is shown in equation (2).

$$yh_8 + (1-y)h_2 = h_3, \quad (2)$$

where y is the fraction of steam extracted from the turbine.

For the case of turbine power, heat transferred in the condenser and the boiler, the energy balances were applied, resulting in equations 3, 4 and 5 respectively.

$$w_{turbine} = (1-y)(h_5 - h_9) + (h_5 - h_8) \quad (3)$$

$$q_{condenser} = (1-y)(h_9 - h_1) \quad (4)$$

$$q_{boiler} = (h_5 - h_4) \quad (5)$$

Additionally, the thermal efficiency of the process was calculated as a function of the vapor fraction as shown in equation 6 below.

$$n_{ther} = 1 - \frac{(1-y)(h_9 - h_1)}{(h_5 - h_4)} \quad (6)$$

On the other hand, for the study of the second law of thermodynamics that allowed calculating the destruction of exergy by components and the exergetic efficiency of the process, a source temperature of 1300 K and of the sump of 303 K was considered, with a reference temperature of T_0=298.15 K. For each component, the exergy destroyed was determined by equation 7.

$$x_{destr,component} = T_0 \left(\Delta s - \frac{q_{in}}{T_{supply}} \right) \quad (7)$$

Therefore, the irreversibility of the cycle was estimated by equation 8.

$$x_{destr,ciclo} = \sum x_{destr,components} \quad (8)$$

1. RESULTS AND DISCUSSIONS

The Rankine cycle studied consists of a boiler with a heating process, a turbine with steam expansion, a condenser, two pumps, and an open feed water heater as shown in Figure 1, which shows the simulation of the designed process.

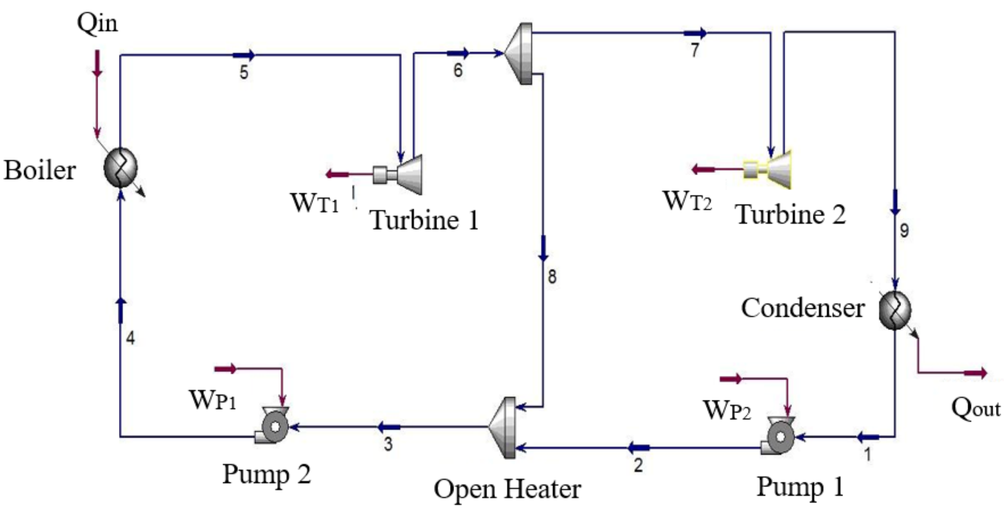


Figure 1. Representation of the Regenerative Rankine Cycle in the Unisim software.

The initial parameters for the cycle analysis were T_1=45.81 °C, P_5=10000kPa, T_5=500°C, P_6=500kPa, P_7=10kPa, T_{source}=1300 K and $T_{environment}$=303K, which were considered to obtain with the Peng-Robinson fluid package all the thermodynamic states of the process, whose results are shown in detail in Table 1, highlighting the phase in which the substance is for the nine process states.

Table 1. Properties of the Regenerative Rankine Cycle

State	Presure *[kPa]*	Temperature *[K]*	Enthalpy *h [kJ/kg]*	Entropy *s [kJ/kg-K]*	Phase
1	10	319,16	-15797,2384	3,2750	Saturated Liquid
2	500	319,17	-15796,7441	3,2750	Compressed liquid
3	500	421,54	-15345,6198	4,4991	Saturated Liquid
4	10 000	422,44	-15335,1253	4,4991	Compressed liquid
5	10 000	773,15	-12606,1995	9,2733	Saturated Steam
6	500	425,00	-13316,6762	9,2733	Mix (x=0,9450)
7	500	425,00	-13316,6762	9,2733	Mix (x=0,9450)
8	500	425,00	-13316,6762	9,2733	Mix (x=0,9450)
9	10	319,16	-13882,8504	9,2733	Mix (x=0,7933)

From the results obtained, the polytrophic efficiency of the pumping and expansion stages of the process were modified to values between 100% and 70%, which implied an increase of 42.85% and 85.21% in the power consumed by pumps 1 and 2 respectively, which is due to the fact that part of the energy will be lost in the form of heat, while the turbine will deliver x% less power, causing a decrease in the efficiency of the process to 29.76%, as shown in table 2, results that show the degree of sensitivity of this parameter on the energy performance of the process, which implies that the frequency of the maintenance plans of the system components significantly impacts the plant's operating costs.

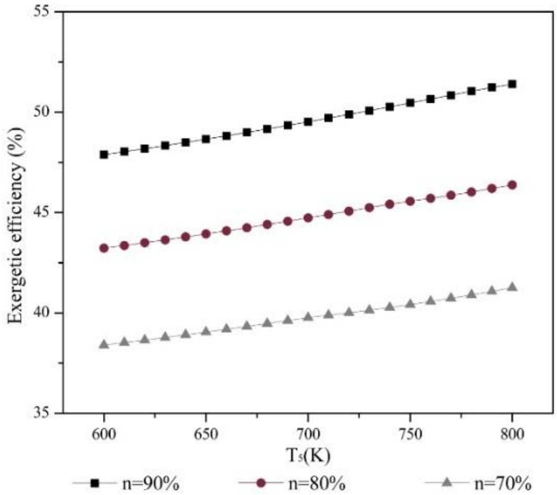
Table 2. Energy Balance Sheet Results

Component efficiency [%]	W Turbine [kW]	W Pump 1 [kW]	W Pump 2 [kW]	Q in[kW]	Q out[kW]	Thermal efficiency [%]
100	150228,97	51,76	1343,29	349302,51	200468,59	42,61
95	143597,62	54,49	1416,07	348399,89	206272,83	40,79
90	136873,62	57,51	1496,95	347488,87	212169,72	38,94
85	130056,98	60,90	2520,12	345635,22	218159,25	36,88
80	123170,63	64,70	4436,12	342888,30	224218,49	34,61
75	116268,52	69,01	6603,60	339889,40	230293,49	32,24
70	109331,98	73,94	9088,26	336572,70	236402,93	29,76

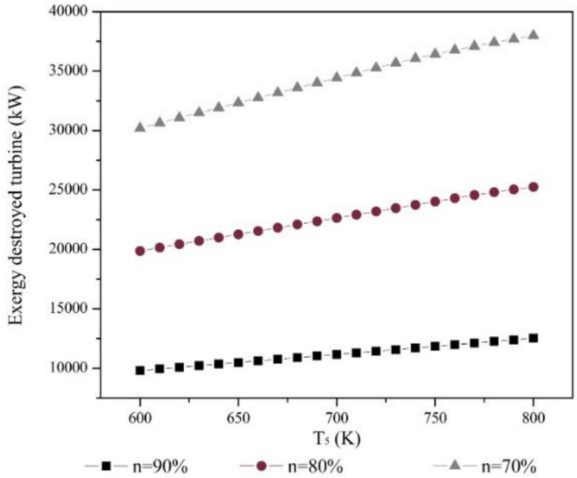
Influence of the temperature at the turbine inlet on the exergetic efficiency and the exergy destroyed.

By analyzing the behavior of the exergetic efficiency when the temperature at the turbine inlet is varied (T_5) in a range of 580 K to 830 K, and also by varying the efficiency of the turbine and the pumps in the same proportion, the graphs shown in figure 4 were obtained as a result, it was also studied, with the same initial parameters, how it influences the destroyed exergy of the turbine.

As shown in Figure 2, obtained by graphing the results provided by the software, we can see that they tend to behave linearly, which can be explained by the influence of the T_5 variable, which generates a proportional change in the exergy destroyed and the exergetic efficiency of the cycle. On the other hand, a 60% increase in the inlet temperature of the turbine generates a higher exergistic efficiency in the system by working at any of the 3 efficiencies in the 70%, 80% and 90% components, but by decreasing the efficiency of the turbine and the pumps from 90% to 70% a considerable decrease in the exergistic efficiency of the system can be observed as shown in Figure 2a.



(a)



(b)

Figure 2. Effect of T_5 variation on, **a)** exergetic efficiency, **b)** exergy destroyed in the Turbine.

However, this 60% increase in temperature at the turbine inlet generates greater exergy destroyed in the turbine, and this effect is most noticeable when the efficiency of the components is less than 90%, as shown in Figure 2b. A comparative analysis of Figures 2a and 2b can lead to the conclusion that it is advisable to work at high efficiency in order to reduce the exergy destroyed in the turbine and increase the exergetic efficiency of the cycle, which leads to improvements in network output and thermal efficiency.

Influence of the source temperature on the exergetic efficiency and the exergy destroyed in the boiler.

The temperature of the source and the efficiency of the components were varied in the same proportion, in order to evaluate the behavior of the exergetic efficiency of the system, the influence on the destroyed exergy of the boiler was also analyzed with the same parameters, as shown in Figure 3.

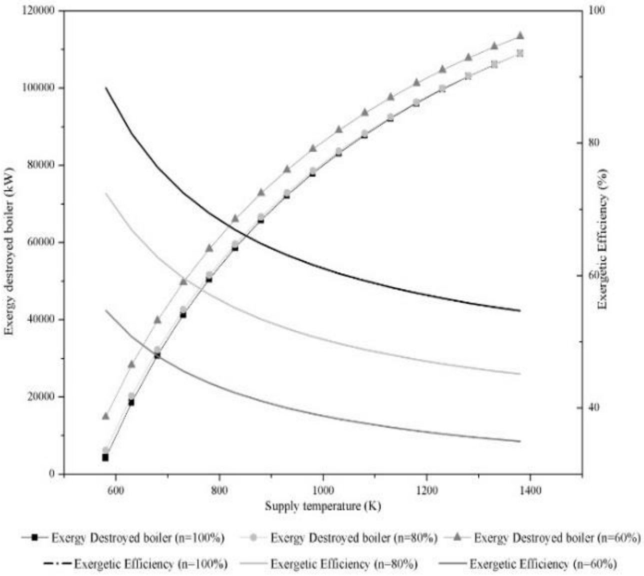


Figure 3. Effect of source temperature variation on the boiler's destroyed Exergy and the Exergetic Efficiency.

The results show an exponential decrease in the exergetic efficiency compared to the increase in the temperature of the source and the efficiency in the turbine and the pumps, this could be due to the fact that the decrease in the work in the turbine plus the increase in the temperature of the source causes more entropy generation. There is also an increase in boiler exergy destroyed exponentially when the efficiency of the turbine and pumps is lower and the temperature of the source increases, leading to higher heat losses and lower thermal efficiency, although it is most noticeable when the efficiency of the turbine and pumps is less than 80%.

CONCLUSIÓN

For optimum performance conditions in the Rankine cycle the inclusion of an open feed water heater improves thermal efficiency, this is because regeneration raises the average temperature at which heat is transferred to the steam in the boiler by increasing the temperature of the water before it enters the boiler. Cycle efficiency is further increased by increasing the number of feed water heaters, which is supported when they are considered economical.

By developing an analysis of the behavior and influence of the source and turbine inlet temperatures on the exergetic efficiency of the Rankine water vapor regeneration cycle, it is observed that this is reflected in the production of mechanical energy useful for creating electrical energy, since a variation in these parameters could cause job losses in the turbine and heat in the boiler, which in turn leads to a decrease in the thermal efficiency and network of the system. The results obtained through the Unisim software, allow to reflect the importance of the working temperatures at source and at the turbine to reduce the exergy destroyed in the cycle and increase the exergetic efficiency of the system.

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