

# Analysis of R134a Organic Regenerative Cycle

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## Abstract

The analysis of organic regenerative cycles is necessary to verify the possibilities of increasing the work and efficiency of a thermodynamic cycle according to some control parameters. The results obtained from this work can be beneficial in several areas such as solar thermal energy. Simulations of an organic regenerative cycle with up to 4 extractions were carried out in order to analyze the behavior of maximum efficiency and the work generated in the turbine. R134a was used as an organic fluid, used in low temperature cycles. Evaporation temperature data between 60°C and 100°C and superheat temperatures equal to 120°C, 200°C and 300°C were tested for cycle analysis. Thus, it was possible to verify the work behavior and maximum efficiency depending on the number of extractions, superheating temperature and evaporation temperature. The models and simulations were made using the Engineering Equation Solver (EES) software and the results were analyzed in Excel. It was concluded that the maximum efficiency increases with the increase of the evaporation temperature and the number of extractions and decreases with the increase of the superheat temperature. The turbine work grows by increasing the evaporation and superheat temperatures, but decreases with the increase in extractions.

## Keywords

Solar Energy, Regenerative Organic Rankine Cycle, R134a Refrigerant

## 1. Introduction

The organic Rankine cycle (ORC) is one of the best technologies for converting low or medium temperature energy sources into electricity. The main problems with the use of the Rankine organic cycle are: low energy efficiency, limitations in increasing output work, working fluid selection, environmental effect and temperature combination between hot and cold flows in heat exchangers [1].

The average thermal efficiency of the ORC system ranges from 0.02 to 0.11; Small systems below 5 kW have lower thermal efficiency. The thermal efficiency of the ORC system depends on the system components, working fluid, heat source, heat sink and cycle operating conditions [2]. To solve these low thermal efficiency problems, different configurations have been introduced in relation to the organic Rankine cycle, including medium preheat organic cycle, regenerative cycle, dual evaporator cycle and ejector cycle [1].

As a derivation of the Rankine cycle, the regenerative cycle uses the reheating of the fluid after the condenser exits, increasing the average temperature of the heat source, which in turn translates into an increase in its thermodynamic efficiency compared to Conventional Rankine cycle. The reheating of the working fluid is achieved by heat exchange through small fractions of steam released by the turbine throughout the expansion process.

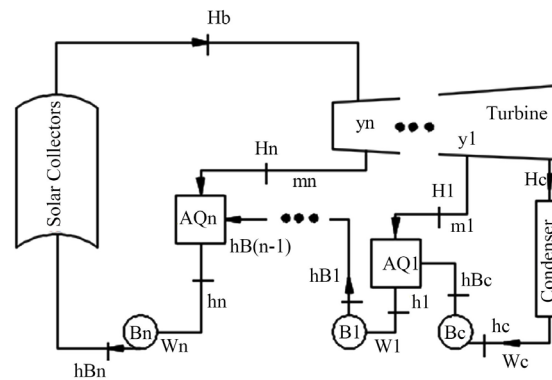
**Figure 1** illustrates a regenerative cycle with “ $n$ ” partial steam extractions throughout the turbine connected to direct contact feedwater heaters (mix heaters). As noted, the regenerative cycle is formed by the set of solar collectors (replacing a boiler), turbine, condenser, direct contact mix heaters and pumps.

These regenerative cycles can easily be used in solar thermal plants with direct or indirect steam generation, *i.e.* with or without a heat exchanger between the collectors and the cycle itself. In this way, the thermal energy of the steam leaving the solar collector field is converted to mechanical energy in the turbine and electrical energy in a generator. The regenerative process prevents low temperature water ingress into the collector field, thereby improving its operating conditions and overall cycle efficiency. The circulating working fluid in the cycle cools and to decrease irreversibility associated with energy exchange with external heat sources in the preheat region, *i.e.* decrease temperature difference to decrease irreversibility, small amounts of water vapor are extracted along the steam turbine expansion to preheat the condenser outlet fluid.

In the regenerative cycle, there are irreversibilities due to the mixing of a sub-cooled liquid with a biphasic, saturated or overheated fluid of higher temperature. According to Bejan (1988) [3], due to these irreversibilities, the efficiency of the regenerative cycle depends on the distribution of turbine vapor extractions, that is, on the temperature difference between a mixture heater and the adjacent heater.

The problem of determining the optimal distribution of a finite stage heater is an important topic regarding steam turbine power plant designs. Vieira da Cunha and Fraidenraich (2012) [4] carried out an analysis of the regenerative cycle with up to three extractions aiming at a “Carnotization” of the Rankine cycle and, observes that after the third withdrawal, only a small increase of benefit in the cycle yield is obtained.

The Organic Rankine Cycle (ORC), unlike the conventional Rankine cycle that uses water as its working fluid, uses an organic fluid. The Conventional Rankine Cycle or Real Rankine Cycle equations are valid for the Organic Rankine Cycle (ORC).



**Figure 1.** Regenerative Rankine cycle with “n” turbine extractions.

The utilization of the organic Rankine cycle dates back to the 19<sup>th</sup> century and since then the number of systems in industrial operation has increased, especially in geothermal applications, waste heat recovery, biomass combustion and solar energy [5].

A model of a parabolic sink power generation system using organic Rankine cycle was developed by He *et al.* (2012) [6]. The model was built on the TRNSYS program considering the integration of several submodels: solar collector, single tank thermal storage, auxiliary power system and heat-electricity conversion system. With this model, the effects of several important parameters were analyzed: vacuum in the absorber tube, high temperature oil flow, solar radiation intensity and incidence angle. His analysis shows that the heat loss of the solar collector increases sharply until it reaches a constant value. The ideal volume of the thermal storage system is found to depend substantially on the intensity of solar radiation.

Gang *et al.* (2010) [7] designs a low temperature parabolic cylinder solar collector electric generation system with a regenerative Organic Rankine Cycle (ORC). The configuration used effectively reduces the irreversibility of heat transfer and allows the use of phase shifting thermal storage. The effects of the regenerative cycle on collector, ORC and overall electricity efficiency were analyzed. The results indicate that the regenerative system has positive effects on ORC efficiency, but negative effects on the collector efficiency due to the increase of the average working temperature of the first stage collectors. The analyses show that there is maximum efficiency for ORC electrical generation under constant irradiance, evaporation temperature and ambient temperature conditions, varying the regenerative cycle mix heater temperature. It concludes that the optimization of the solar-electric generation ORC regenerative cycle differs from a conventional ORC.

ORC studies are common to find in the literature, they analyze working fluids for different ranges of operation and applications for certain purposes [8] [9] [10]. This article approaches something different, an analysis of a fluid widely used in ORC with the purpose of increasing the efficiency of the cycle. The quest to increase the efficiency of a cycle is important as a way of saving fuel. When it comes to a cycle with solar energy source, the resource is limited by space and

radiation conditions, motivating the analysis of more efficient steam cycles. This article then discusses the ideal conditions for an R134a ORC cycle for maximum efficiency, depending on the evaporation temperature, the superheating temperature, number of extractions and the position of these extractions. It also addresses an approximate way of obtaining a distribution of extractions for the purpose of maximum efficiency.

## 2. Equations Model

The equations for work (turbine) and regenerative cycle efficiency are based on [4]. They demonstrate the energy and mass balances of each cycle component illustrated in **Figure 1**. For the work per unit of mass (referring to the mass flow in the output of the collectors), considering “ $n$ ” extractions (wt [kJ/kg]) we use the expression:

$$w_t = \frac{\dot{W}_t}{\dot{m}_b} = (H_b - H_c) + y_n(H_c - H_n) + \dots + y_1(H_c - H_1) \quad (1)$$

where  $\dot{m}_b$  is the total mass flow through the manifolds [kg/s],  $\dot{W}_t$  the turbine power [W],  $H_n$  is the enthalpy at the outlet of the turbine extractions,  $H_b$  the enthalpy at the boiler outlet and  $H_c$  the enthalpy at the condenser inlet and  $y_i$  is the mass fraction of the  $i$ -th extraction. The mass fraction  $y_i$  is the ratio between the extracted mass flow ( $\dot{m}_i$ ) and the mass flow at the collector inlet ( $\dot{m}_b$ ), *i.e.*,  $y = \dot{m}_i / \dot{m}_b$ . For the second extraction onwards, the mass fraction is calculated by:

$$y_i = \frac{(h_i - h_{B(i-1)})}{(H_i - h_{B(i-1)})} \left(1 - \sum_{j=i+1}^n y_j\right) \quad (2)$$

where  $h_j$  is the enthalpy at the exit of the  $i$ -th heater and  $h_B$  is the enthalpy at the outlet of each pump. The mass fraction for the first extraction ( $i = 1$ ) is expressed as:

$$y_1 = \frac{(h_1 - h_{Bc})}{(H_1 - h_{Bc})} \left(1 - \sum_{j=i+1}^n y_j\right) \quad (3)$$

The total heat per unit mass (referenced by the total mass in the collectors -  $m_b$ ) of the collector set ( $q_b$  [J/kg]) and the condenser ( $q_c$  [J/kg]) is directly proportional to the enthalpy difference, *i.e.*:

$$q_b = H_b - h_{Bn} \quad \text{and} \quad q_c = (h_c - H_c) \left(1 - \sum_{i=1}^n y_i\right) \quad (4)$$

The efficiency of the regenerative cycle is expressed by the ratio of net work and the heat absorbed in the collectors ( $q_b$ ), both per unit mass of the cycle ( $m_b$ ):

$$\eta_t = \frac{w_t - \sum_{i=1}^n \left[ \left(1 - \sum_{j=i+1}^n y_j\right) |w_{Bi}| \right] - |w_{Bc}| \left(1 - \sum_{j=1}^n y_j\right)}{q_b} \quad (5)$$

where  $w_t$  and  $w_B$  are the turbine and pump work, respectively, per unit mass ( $m_b$ ) [J/kg]. Pump work can be calculated by multiplying the pressure difference

they are subjected to by the respective specific fluid volume in the region [11].

### 3. Organic Fluids

Organic fluids can be classified according to their temperature range: Low, Medium or High Temperature. Low temperature organic fluids operate below 150°C and are generally used for geothermal energy recovery or low quality thermal waste. In this range machines can be found that operate from 80°C to 150°C and others from 60°C to 120°C.

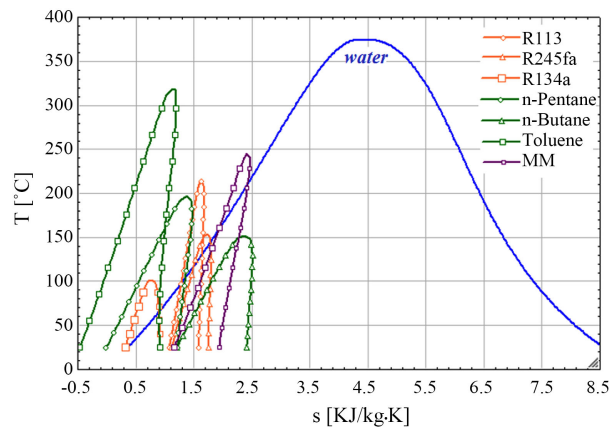
Medium temperature organic fluids operate between 150°C and 300°C and are generally used for combustion heat recovery from biomass products. High temperature organic fluids operate above 300°C and are ideal for heat recovery from thermal machines (gas or diesel) and other higher quality thermal waste. These machines generally operate at temperatures in the order of 350°C, requiring a thermal power supply in the order of 900 kWe to produce 165 kWe [5].

In commercial applications the following organic fluids are found: Ammonia (R-717); R-134a (HFC), used in geothermal power plants; R-245fa (HFC) for low temperatures; N-pentane, used at the commercial solar-powered ORC plant in Nevada, USA; Solkatherm (SES36) which is an azeotropic mixture; Toluene for recovery at higher temperatures; Hydrocarbons (HCs), Hydrofluorocarbons (HFCs), Hydrofluoroethers (HFEs) and OMTS (octamethyltrisiloxane) [5].

Certain characteristics are important for choosing an organic fluid in ORC Organic Rankine Cycle, such as: 1) Zero or positive slope ( $ds/dT$ ) saturated vapor curve. In these cases the fluids are termed as isentropic or dry fluids; 2) high latent heat of vaporization; 3) low specific volume (in the liquid-vapor phase); 4) high specific heat; 5) moderate critical parameters (temperature and pressure); 6) operating pressures (condensation and vaporization) between 1 and 25 bar respectively; 7) Good heat transfer properties (low viscosity, high thermal conductivity, etc.); 8) Good thermal and chemical stability (stable at high temperatures); 9) Good compatibility with other materials (non-corrosive, etc.); 10) Good safety characteristics; 11) Low environmental impact (Low Ozone Depletion Potential, ODP and Low Global Warming Potential, GWP); and 12) Low cost and availability.

**Figure 2** shows the temperature ( $T$ ) versus entropy ( $s$ ) diagram of water and some organic fluids: R113, R245fa, R134a, n-pentane and n-butane. In it we observe the operating temperature ranges of these fluids in a Rankine cycle, below the critical point. The R134a, for example, has a lower operating range than water, a maximum temperature of 100°C [12]. Fluids that have the saturated vapor line very close to a vertical line are called isentropic fluids.

It is also observed that the behavior of the temperature versus entropy diagram of the organic fluids is different from the water diagram because the saturated steam line slope ( $ds/dT$ ) is zero or has a negative value. Consequently, a turbine expansion in the Rankine cycle, the fluid enters in the vapor phase and after an isentropic expansion, leaves the turbine in the vapor state, unlike the water that in the turbine extraction the fluid is in a biphasic state.



**Figure 2.** Temperature versus entropy diagram of water and some organic fluids.

Bha and Zhao (2013) [13] review work fluids used in the organic Rankine cycle, under the emphasis of the influence of thermodynamic and physical properties and performance on the Rankine organic cycle. They also compare applications of pure and mixed organic fluids across the operating characteristics of expansion machines.

Baral and Kim (2014) [14] analyzed 15 (fifteen) thermodynamically organic fluids in an Organic Rankine Cycle, evaluating the performances and aptitudes of each fluid. Of these 15 (fifteen) fluids, the RC318 and R123 offered very attractive performance, but require environmental precautions due to the high ozone depletion power and high global warming power. Fluids R134a and R245fa were the most appropriate for low and medium temperature Organic Rankine Cycle Solar Cogeneration Systems. The choice of these organic fluids, suitable for ORC plants, was based on desirable characteristics such as; adequate critical low temperature and pressure; low specific volume, low viscosity and surface tension; high thermal conductivity; adequate thermal stability; non-corrosive; non-toxic and compatible with turbine material and lubricating oil.

Analyses by Lakew and Bolland (2010) [15], Sauret and Rowlands (2011) [16] and Gu and Sato (2002) [17] also emphasize that R134a fluid is a good working fluid and meets the stated requirements. These last three work citations also consider the use of R134a organic fluid in Rankine cycles operating under supercritical conditions, *i.e.* above the critical point conditions (Critical Temperature and Pressure).

After analyzing the possible organic fluids that could be used, R134a was chosen for its acceptance in the literature and its good thermophysical and environmental characteristics.

## 4. Results and Discussions

The simulations were based on models elaborated in the computer program Engineering Equation Solver (EES), software capable of solving equations in general and used in thermodynamics, with a database of thermophysical properties of

fluids. For each number of extractions, a different model and for each model, the simulation consists of sweeping all the possible efficiencies extracted along the various extraction points of the turbine. The maximum efficiency value is considered as the optimal point of the cycle. For cycle models with more than two extractions, combinations of turbine extraction pressure values are extracted and only the combination providing the maximum efficiency value is considered.

The simulations reveal that there is a maximum efficiency value as a function of the turbine extraction points, considering the other parameters as constants. **Figure 3** shows two efficiency graphs as a function of turbine extraction pressures for organic fluid R134a with evaporation temperature of 85°C, overheat temperature of 140°C and condensation pressure of 10 kPa for organic ORC with two extractions. It can be observed that there is a unique maximum value of the efficiency in function the extractions pressures of mixing heaters. The same event is true for other regenerative cycles.

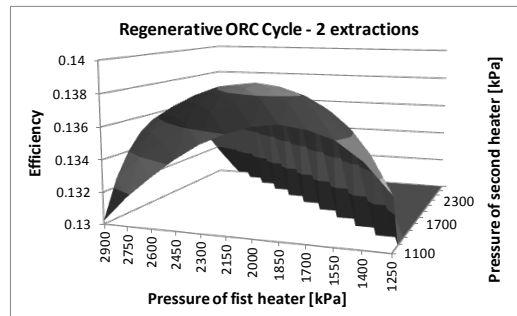
The thermophysical properties of R134a generated by the EES program were compared with data provided by Huber and McLinden (1992) [18], with relative difference values less than 1%. The critical temperature of R134a is 101.08°C; a fluid used for low temperature systems. The condensing pressure used for the organic Rankine Organic Regenerative Cycle was 1000 kPa, which corresponds to an approximate saturation temperature of 40°C.

The evaporation temperatures ( $T_{ev}$ ) of the cycle ranged from 60°C to 100°C, while for the superheat temperature ( $T_{sup}$ ) the following values were adopted: 120°C, 140°C, 160°C, 180°C, 200°C and 300°C. It has not extended to superheating values above 300°C since it is observed that the cycle efficiency decreases when the superheating temperature is increased. Graphs for superheating temperatures from 140°C to 180°C are not included in this article because of the space constraint and do not represent a different behavior than expected when changing superheating temperature from 120°C to 200°C.

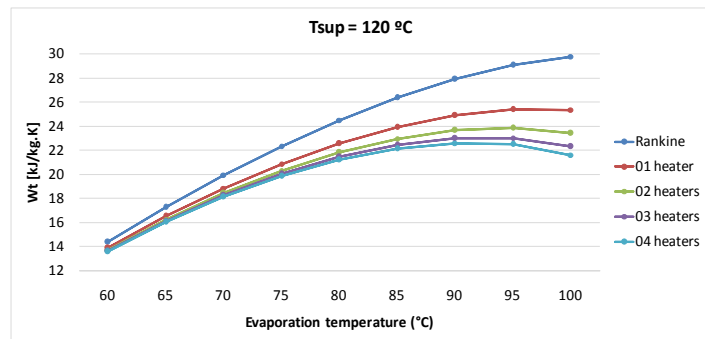
**Figures 4-6** analyze the working behavior of the turbine for the conventional Rankine and ORC regenerative cycles with up to four extractions as a function of evaporation temperature ( $T_{ev}$ ) and superheating ( $T_{sup}$ ). It is noteworthy that the value of the work is at the point of maximum efficiency of the cycle.

It can be noted that for low superheat temperatures ( $T_{sup}$ ), as in the case of **Figure 4**, the work increases with the evaporation temperature ( $T_{ev}$ ), until reaching a maximum value and then begins to reduce. For higher  $T_{sup}$ , **Figure 4** and **Figure 5**, there is a linearization of the work curves that continue to grow until the  $T_{ev}$  finds its maximum value. It was also noticed that for high  $T_{sup}$  values, the value of work varies little in relation to the number of extractions.

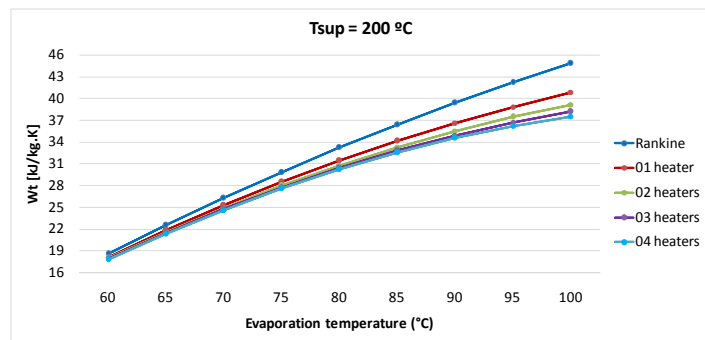
**Figures 7-9** show the efficiency behavior as a function of the number of extractions and the evaporation temperature ( $T_{ev}$ ) for superheat temperatures ( $T_{sup}$ ) of 120°C, 200°C and 300°C, respectively. As the  $T_{ev}$  is increased, the vertical distance between each curve becomes greater, making it visible that when the evaporation temperature is increased, the efficiency also increases, without having a maximum value.



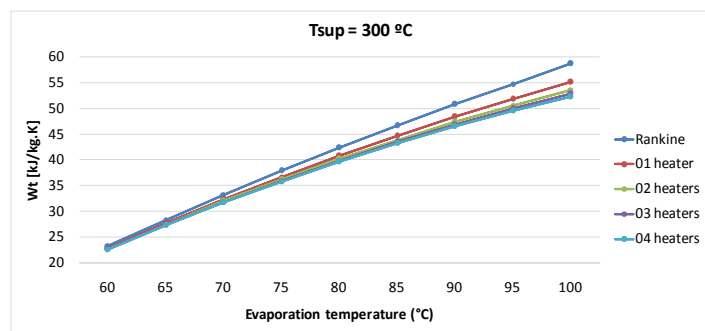
**Figure 3.** Efficiency of the regenerative ORC cycle as a function of the turbine extraction pressures for two extractions cycle.



**Figure 4.** R134a regenerative ORC Turbine work up to 4 extractions with 120°C superheating.

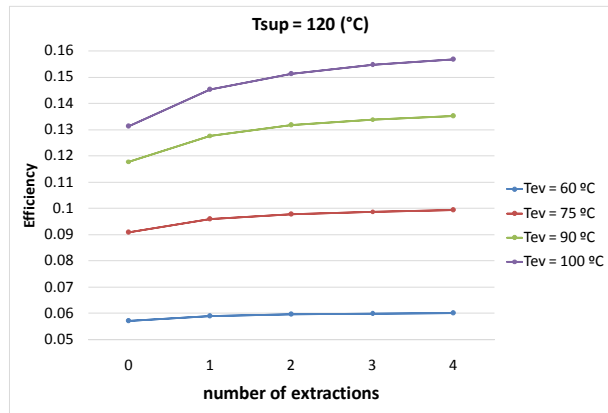


**Figure 5.** R134a regenerative ORC Turbine work up to 4 extractions with 200°C superheating.

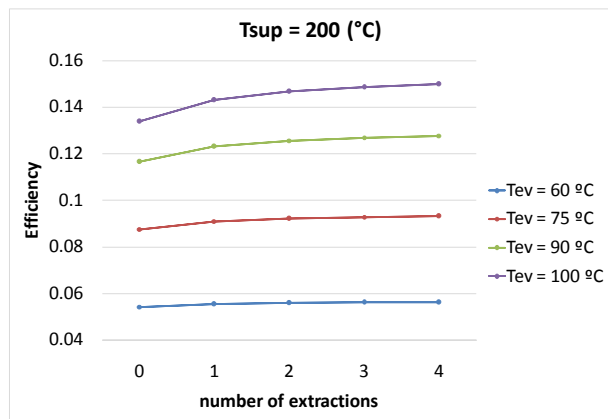


**Figure 6.** R134a regenerative ORC Turbine work up to 4 extractions with 300°C superheating.

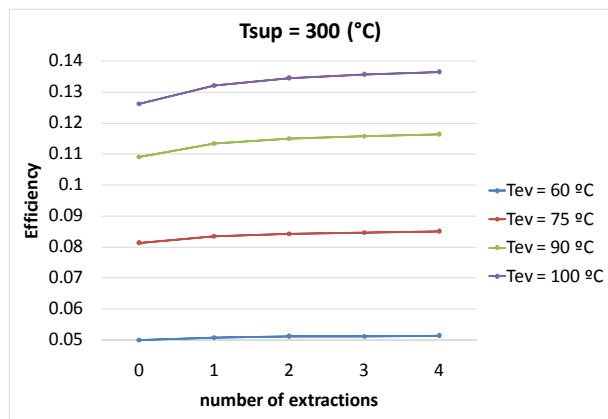




**Figure 7.** Efficiency of R134a regenerative ORC up to 4 extractions with 120°C superheating.



**Figure 8.** Efficiency of R134a regenerative ORC up to 4 extractions with 200°C superheating.



**Figure 9.** Efficiency of R134a regenerative ORC up to 4 extractions with 300°C superheating.

The graphs in **Figures 6-9** show the increase in efficiency of the regenerative cycle with the increase in the number of extractions. For the three cases (superheat temperature 120°C, 200°C and 300°C), efficiency has a small increase, around 5%, for low evaporation temperature situations ( $T_{ev} = 60^\circ\text{C}$  and  $75^\circ\text{C}$ ).

In **Figure 7**, there is an increase of approximately 11% in the first extraction, with  $T_{ev} = 100^\circ\text{C}$ , and of approximately 5% in the second; and for  $T_{ev} = 60^\circ\text{C}$  the increase in efficiency is approximately 3% for the first extraction and 1% for the second.

It is also observed that the increase in efficiency is greater until the second extraction. The efficiency gain after the third extraction is not so attractive, being noticed for evaporation temperature above  $75^\circ\text{C}$ .

It can be concluded with the graphs of **Figures 4-9** that, from the point of view of the work of the turbine, it is interesting to use a high value for  $T_{sup}$  if you are using a regenerative cycle, because this way you get a higher work, although the cycle would not be working at maximum efficiency, as extractions reduce the work generated by the turbine. When the efficiency is maximum for the cycle with 1 extraction in the turbine,  $T_{sup} = 120^\circ\text{C}$  and  $T_{ev} = 100^\circ\text{C}$ , the total work is  $W_t = 25.38 \text{ kJ/kg}\cdot\text{K}$ . Whereas in **Figure 6**, where  $T_{sup} = 300^\circ\text{C}$ ,  $W_t = 55.16 \text{ kJ/kg}\cdot\text{K}$ , that is, more than double the work performed. However, the efficiency in the first case is 14.52% and 13.21% in the second (see **Figure 7** and **Figure 9**), that is, although the cycle is performing more than twice the labor value, it is not working at maximum efficiency.

In a regenerative cycle with superheated steam, the irreversibility of the mixture heaters derives from the mixture of a subcooled liquid with a biphasic, saturated or overheated fluid. According to [3], due to these irreversibilities, the efficiency of the regenerative cycle depends on the distribution of the mixing heaters, mainly the temperature difference between the two adjacent heaters. Haywood (1949) [19] states that the difference in enthalpy at the outlet of a mixing heater and in the adjacent one must be constant to obtain maximum productivity. Haywood's theory [19], despite being only approximate, has a simplicity and ability to illustrate the main aspects of the problem which make it a useful and worthwhile introduction to the subject.

The problem of determining the optimal allocation of a finite number of stages is an important topic in steam turbine plant designs. Souza (1980) [20] conducted a graphical analysis of the performance of this regenerative cycle with several extractions in order to "carnotize" the Rankine cycle. In his analysis, he notes that after 3 mixing heaters a small increase in cycle efficiency is obtained.

An investigation into [19] claims was made to ascertain when the efficiency of the regenerative cycle is at maximum. The first hypothesis to be analyzed is whether the enthalpy variation before and after the mixing heater, as well as for the condenser, are constant, that is, they have equal values. Observing the cycle reference in **Figure 1**, this hypothesis is to verify if  $H_c - h_c = H_1 - h_1 = H_2 - h_2 = \dots = H_n - h_n$ . The second hypothesis is to analyze whether the enthalpy variations at the outlet of each adjacent mixing heater are equal and whether the enthalpy variation at the outlet of the last heater with the enthalpy at the condenser outlet is a multiple of the enthalpy variation of the adjacent heaters.

The analyzed results show that the variation of enthalpy through the mixing heater ( $H_i - h_i$ ) increases with the evaporation temperature. Between any two

heaters, the “ $H_i - h_i$ ” difference is less than 10% for evaporation temperatures between 60°C and 85°C and, for values between 85°C and 100°C, this difference is less than 30%. **Table 1** shows the maximum “ $H_i - h_i$ ” variation, in percentage terms, between any two heaters as a function of the evaporation and superheat temperature for the organic regenerative cycle R134a of two and four extractions.

The data shown in the **Table 1** indicate that Haywood’s hypothesis [19] isn’t true, the increase in enthalpy through heater isn’t constant to have maximum cycle efficiency and there are variation due to evaporation and superheating temperature. Larger relative deviations occur only for evaporation temperatures above 85°C and superheating temperature of 120°C and 200°C. The best relative values presented are for superheat temperature of 300°C, indicating that high superheat temperature is also important for an enthalpy uniformity throughout the heater.

Another assumption made in [19] analytical is to consider the enthalpy difference between two adjacent heaters ( $h_i - h_{i+1}$ ) as constant to have maximum efficiency. This hypothesis was analyzed in this work and it is noted that the difference enthalpy “ $h_c - h_b$ ” ( $h_c$  outlet condenser and saturated liquid in collectors  $h_b$  saturated liquid in collectors) divided by the number of heaters ( $n$ ) is practically equal to the difference in enthalpy between each adjacent heater ( $h_i - h_{i+1}$ ). **Table 2** shows the results of maximum relative values of  $(h_i - h_{i+1})/[(h_c - h_b)/n]$  for R134a organic regenerative cycle of two and four extractions.

**Table 1.** Increased enthalpy through the heater: maximum relative variation between mixing heaters.

Evap. Temp.	Superheating Temp/02 extractions			Superheating Temp/04 extractions		
	120°C	200°C	300°C	120°C	200°C	300°C
60°C	2.6%	1.4%	0.6%	4.8%	2.9%	1.1%
70°C	4.7%	2.5%	1.2%	8.0%	5.3%	2.2%
80°C	5.9%	3.9%	2.0%	10.0%	8.0%	3.6%
90°C	11%	5.8%	3.0%	20.0%	12%	5.4%
100°C	18%	8.4%	4.3%	30.0%	18%	8.0%

**Table 2.** Enthalpy difference between heaters: maximum relative variation.

Evap. Temp.	Superheating Temp/02 extractions			Superheating Temp/04 extractions		
	120°C	200°C	300°C	120°C	200°C	300°C
60°C	1.8%	2.8%	1.9%	3.0%	4.9%	1.6%
70°C	3.1%	4.3%	5.6%	3.1%	5.1%	7.1%
80°C	4.0%	5.1%	7.4%	5.2%	5.9%	7.4%
90°C	5.0%	7.2%	9.1%	5.7%	9.2%	13.3%
100°C	5.9%	9.6%	11.0%	9.4%	12.1%	15.4%

**Table 2** reports that for evaporation temperature below 80°C the relative difference in enthalpy between adjacent heaters is less than 8%, demonstrating that the distribution of heaters is almost uniform for maximum efficiency.

In general, a way to obtain an efficiency close to the maximum value for an organic regenerative cycle with R134a is to divide the enthalpy difference between the saturated liquid at the condensing pressure (condenser outlet) and evaporation pressure (Boiler) and divide by number of turbine extractions (number of mixing heaters), positioned the heaters in these positions. In this way the extraction pressure can be found considering saturated liquid at the outlet of the mixing heater.

## 5. Conclusions

Organic Rankine cycles (ORC) and the organic regenerative cycles are already applied several areas as thermal solar energy, but under conditions with only with one extraction. In order to better understand the behavior of the organic regenerative cycle, simulations of this cycle were carried out with up to 4 extractions of the turbine, using R134a, a fluid for low temperatures, as the working fluid. The evaporation temperatures were conducted between 60°C and 100°C, while the superheat temperature was considered 120°C, 200°C and 300°C. Thus, it was possible to verify the work behavior per unit of mass at maximum efficiency and the maximum efficiency values as a function of the number of turbine extractions, superheat temperature and evaporation temperature.

After obtaining the maximum efficiencies and the total work for each cycle (Rankine without extractions, with 1, 2, 3 and 4 extractions) with the working fluid R134a, it was realized that at low superheat temperatures, efficiency has its maximum value. For higher superheat temperatures (300°C) there is no significant variation in efficiency when the number of turbine extractions is increased.

In the same way it was possible to visualize at low superheat temperatures (120°C) that there is a maximum working condition of the turbine that does not characterize that it is at the maximum efficiency point, where the evaporation temperature is 100°C.

In general, the organic fluid R134a has a better efficiency with high evaporation temperatures and low superheat temperatures. Efficiency grows with the increase in the number of extractions; however, this increase is more significant for the first extraction. The total work is at maximum when the superheat temperature increases and the number of extractions decrease.

It was also found that to obtain efficiency close to the maximum value for an R134a organic regenerative cycle is position the heaters under certain conditions: 1) the difference in output enthalpy between each adjacent heater must be equal; 2) the increase in enthalpy through the heaters must be equal. Knowing the enthalpy and under the condition of saturated liquid at the outlet of each heater, the pressure is determined. This results in a uniform enthalpy difference between the mixing heaters.

The study was limited to four extractions of the cycle based on the information that efficiency does not have a significant increase for cycles above three extractions, as well as the fact that the simulation time increases exponentially as one more extraction is added. Other configurations of the cycle can be analyzed in order to increase efficiency, such as, for example, reheating between one extraction and the other. The cycle with other fluids can also be analyzed and compared with the cycle of R134a.

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### Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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