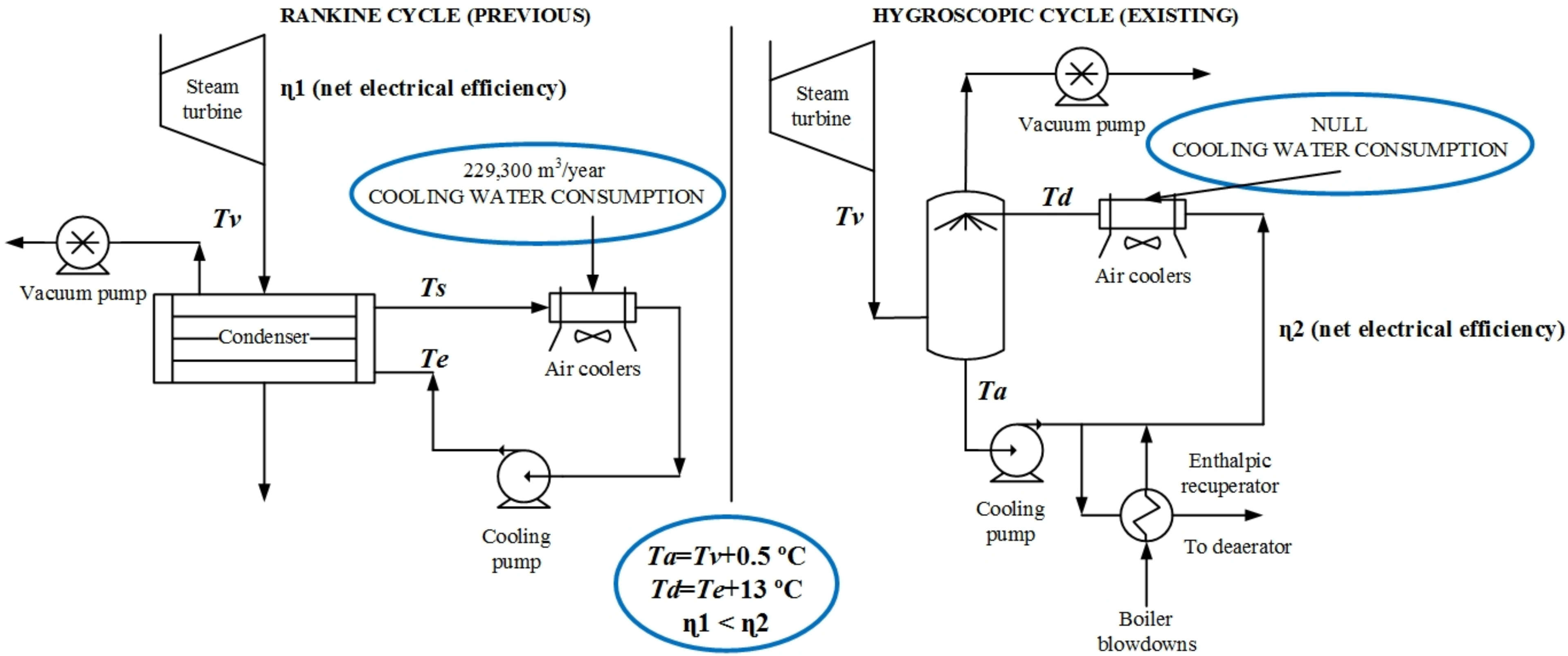
Hygroscopic Cycle Technology incorporated to 12.5-MWe “Vetejar” Biomass power plant.



Advantages of incorporating Hygroscopic Cycle Technology to a 12.5-MW biomass power plant

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Abstract

This article focuses on the advantages found by incorporating Hygroscopic Cycle Technology into the 12.5-MWe "Vetejar" biomass power plant operating in the province of Córdoba (Spain) since 1996. The power plant required upgrades to increase its availability, net electrical performance and to extend the service life span of refrigeration equipment. The incorporation of the new Hygroscopic Cycle Technology has allowed not only to alleviate the shortcomings of the power station in a simple way, but also to make the most of the existing equipment, despite the adverse environmental conditions. The scarcity of water in the area is one of the greatest difficulties the plant has met since its start-up. It significantly diminishes the operation hours of the plant, reducing the electrical power generated, electrical performance and availability. The incorporation of this novel technology to the existing plant has allowed the cooling temperature to increase by 13ºC while maintaining the same condensing pressure. As a result, significant net increase in electrical efficiency, reduction of auto-consumption and cut down on annual cooling water consumption were obtained.

Keywords: Rankine cycle; Efficiency; Steam absorber; Air coolers; Water saving

1. INTRODUCTION

Currently, about 80% of the world's total electricity produced is generated from fossil fuels, while the remaining 20% is obtained from different sources such as nuclear energy, renewable energy, etc. [1].

Because the non-renewable primary energy sources available are not unlimited, it is essential to increase the conversion efficiency as much as possible to optimally exploit the available sources. In order to improve the efficiency of the conversion processes used, numerous improvement techniques are being studied.

One of the most widely used technologies worldwide in the production of electrical energy are steam cycles, including the Rankine cycle, which transform heat into electricity. The main advantage of this cycle is its continuous development which gives it an industrial

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maturity and high applicability [2,3]. The Rankine cycle is widely used in thermoelectric and nuclear power plants, which is why its efficiency has a large impact at the global level, as it directly influences fuel consumption, greenhouse gas emissions and the economic viability of the power plants [4, 5].

The improvement of the Rankine cycle efficiency has been studied for several decades [6,7]. Most common methods used to improve the thermal efficiency of Rankine cycles are called: supercritical, reheated, regenerative and binary vapor cycles. They are mainly based on reducing the losses due to irreversibilities. The goal of each of these methods is not only to increase the efficiency of the ideal Rankine cycle but also to prevent vapor from entering the pump and keeping the quality of the steam at the turbine outlet above 90% [8].

The use of supercritical working fluids [9] or zeotropic mixtures [10, 11] may also increase the Rankine efficiency. Second-law-based thermodynamic analysis of regenerative-reheat Rankine-cycle power plants was done by Habib & Zubair [12]. As a result of incorporating feedwater heating and reheat, an efficiency improvement of 12% and 14% can be achieved respectively.

Most of the systems proposed to increase the efficiency of the Rankine cycle focus on modifying pressure and temperature conditions, improving fuel composition (eliminating, for example, sulfur compounds), materials resistance, improve the design of the turbines used and apply automated control systems.

For the conversion of low-grade heat into power there is a wide room for efficiency improvement [13]. In this sense, Chen et al. [14] proposed a supercritical Rankine cycle using zeotropic mixture working fluids. Results showed that thermal efficiencies of the proposed supercritical Rankine cycle can achieve an improvement of 10-30% over the organic Rankine cycle.

From the environmental point of view, Beér [15] revised electric power generation system development with special attention to plant efficiency. Power generating options, including coal-fired Rankine cycle steam plants and coal gasification combined cycle plants are compared for their efficiency, cost and operational availability. According to this study, efficiency improvement is by far the most predictable and lowest cost method to reduce all emissions.

Recently, innovative designs have been developed in order to increase the efficiency of Rankine cycles for power plants. In the study performed by Zandian & Ashjaee [16] a dry cooling tower and a solar chimney were combined in order to increase the thermal efficiency of a steam Rankine cycle. The results showed a maximum of 0.37 % increase in the thermal efficiency of a 250 MW fossil fuel power plant.

Energy analysis for a Rankine-Kalina combined cycle was performed by Murugan & Subbarao [17]. This cycle produces higher power output and is more efficient than a Rankine steam cycle. The improvement was based on the reduction of losses due to moisture in the turbine exhaust and losses in the condenser of Rankine steam cycle power plant.

Bolatturk et al. [18] conducted a thermodynamic and exergoeconomic study of a thermal power plant in Turkey. The highest amount of exergy loss costs was obtained respectively in the boiler, the turbine group and the condenser. From the exergoeconomic analysis, the highest factor has been measured in the turbine group, which is followed respectively by the boiler and the condenser drain pump.

The previously explained improvements can be combined with a new system with absorption step using hygroscopic compounds [19]. The resulting cycle is called Hygroscopic cycle [20,21]. It is a power cycle similar to the Rankine cycle characterized by working with hygroscopic compounds, which optimize the output steam of a condensing turbine and can work under high vacuum at the output with good refrigeration conditions. In short, with this technology the condensing temperature at a given pressure in the condenser is increased.

One of the problems facing conventional Rankine cycles occurs when refrigeration is to be carried out at high ambient temperatures. In this case, the electrical production of the power plant is reduced considerably or may even be forced to stop production.

The problem is aggravated when there is a shortage of water [22] for cooling at the location of the plant. With the Hygroscopic cycle technology, this problem is solved in a practical and efficient way.

This article details the benefits of incorporating the innovative technology of the Hygroscopic cycle to an existing biomass power plant, which is the first world reference at industrial scale that uses this technology. This cycle allows the 12.5-MW biomass power plant of Palenciana (Córdoba-Spain) to completely eliminate the consumption of cooling water [23], and to significantly reduce the electric auto-consumption. Additionally, the hours of availability at maximum speed of the turbine increase, allowing the power plant to work at full steam load at 45 °C ambient temperature, a value that with the traditional Rankine cycle configuration was unthinkable, and as a result, the net electrical efficiency increases.

The rise in the molality of the entering cooling reflux stream to the Hygroscopic Cycle steam absorber increases the condensing temperature at a given pressure, always greater than the saturation temperature of the pure steam.

This boosts two important advantages of a Hygroscopic cycle over a traditional Rankine cycle:

1. On the one hand, a decrease in the condensing pressure for a given cooling temperature is obtained when using the Hygroscopic cycle instead of a Rankine cycle. This increases the electrical power output of the turbine and the electrical performance [24] of the plant.

2. On the other hand, the Hygroscopic cycle makes it possible to raise the cooling temperature compared to the Rankine cycle for a given condensing pressure. It allows the energy of condensation to be dissipated in dry mode (with an air cooler), instead of in a cooling tower. The benefits are the consequent saving of water [25, 26], tower purges, plumes, and reduction of associated operation and maintenance costs [27]. This water saving [28] is one of the main advantages of using this technology, given the shortage of water foreseen for humanity in the future, and hence the high cost of the latter. This second advantage of the technology is used in the present article.

It is therefore a technology that can replace and improve Rankine cycle for any electrical power generation in the following power plants [29]: combined cycles, thermoelectric plants, biomass power plants and nuclear power plants. Specifically, this paper describes the requirements and limitations of an existing biomass power plant, and the advantages of replacing the current Rankine cycle with the innovative Hygroscopic Cycle Technology (HCT).

Regarding the novelty of this work, it shows the results of a new power cycle (HCT) incorporated for the first time in an actual power plant. The new technology allows the plant to refrigerate the steam even with high ambient temperatures, increasing the net electrical efficiency of the plant, as well as removing the cooling tower and therefore, avoiding cooling water consumption. It is an innovation of great interest for the energy sector, applicable to all power plants that work with a steam cycle. It also presents very relevant information obtained from an actual installation.

2. MATERIALS AND METHODS

2.1 Background of the 12.5-MWe biomass power plant of "Vetejar"

The biomass power plant of "Vetejar" (Steam and Electricity El Tejar), is owned by *Oleícola El Tejar* [30], located in Palenciana (Córdoba -Spain). The plant was commissioned in 1995, with a power generation capacity of 12.5 MWe. It was designed for a steam production capacity of 49,000 kg/h at 87 barg and 495ºC. The biomass used is alperujo [31] with an average humidity of 50%. Inlet steam conditions at the condensing turbine are 85 barg and 480 ºC and pressure outlet ranges between 140 and 240 mbar.

The cooling for the condenser was initially provided by cooling towers. The water entered the tower at 37 ºC and existed at 25 ºC.

Given the scarcity of water in the area, in 1997 a battery of air coolers was installed to achieve significant water savings. Also, an adiabatic spray system [27] was fitted to lower the outlet temperature without significantly reducing the electrical performance when ambient temperatures reach more than 25°C [32]. Environmental conditions are shown on table 1.

Table 1. Environmental conditions in Palenciana (Córdoba, Spain).

Average annual temperature (ºC)	18.2
Average temperature of the warmest month (ºC)	28.0
Maximum average annual temperature (ºC)	25.1
Highest average temperature, of the warmest month (ºC)	36.9
Average annual relative humidity (%)	60

Due to the high environmental temperatures [30], the scarcity of water in the area and the deterioration of the copper battery and aluminum fins of the air coolers because of the spraying of the cooling water, HCT has been incorporated to the biomass power plant. The specific benefits can be summarized as follows:

- Thanks to the new available cooling conditions with HCT, higher annual production is obtained in the turbine by lowering the outlet pressure.
- An increase in the availability of the plant is achieved as the plant depends less on the water shortages of the region at peak ambient temperatures.
- Air coolers have a lower electrical consumption since the new cooling temperature is 13ºC higher than the previous one.
- The overall result for this plant is that it achieves a higher electrical efficiency, without the need of cooling water.

- On top of that, there is no more need for adiabatic cooling at the air-coolers, so there is no more corrosion on them. This extends the life span of the air coolers.

Figure 1. View of the incorporation of HCT at the "Vetejar" biomass power plant.

2.1. Hygroscopic cycle at the biomass power plant of "Vetejar"

The values reflected in the current article were taken from the revamped 12.5-MWe "*Vetejar*" biomass plant located in Palenciana (Córdoba-Spain), to which HCT has been incorporated (Figure 1).

Figure 2 shows the process diagram of Hygroscopic cycle at the "*Vetejar*" biomass power plant.

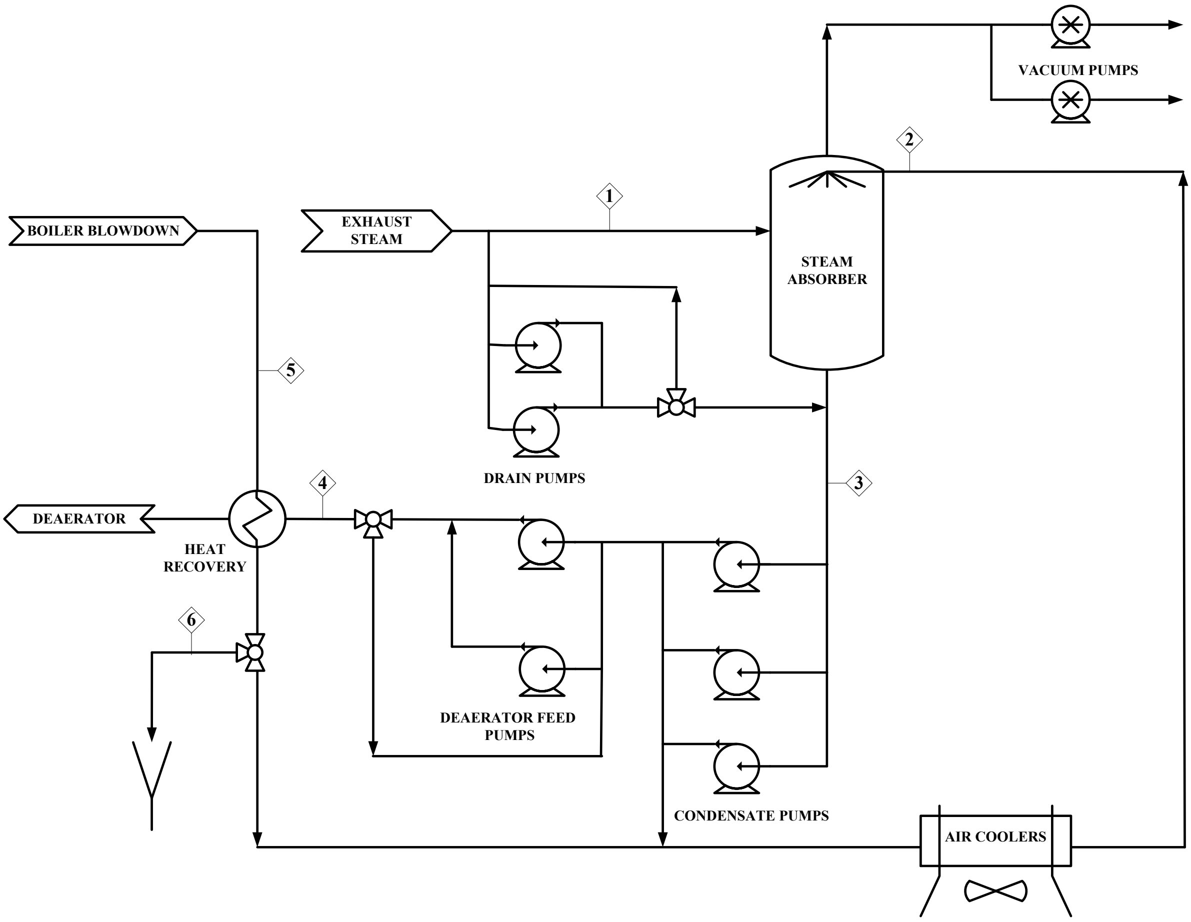

Figure 2. Process diagram for Hygroscopic cycle in "Vetejar".

According to the process diagram shown in Figure 2, the turbine outlet exhaust steam (1) is directed to the steam absorber (Figure 3) where it is brought into contact with a liquid stream of water, which acts as a cooling reflux (2), rich in hygroscopic compounds, and with an electrical conductivity [33] always greater than that of steam. The absorber is connected to a liquid ring vacuum pumps [34] to maintain the vacuum level, both at start-up and during normal operation. These pumps are smaller (with lower electrical consumption) than those used in a surface condenser (i.e. shell-and-tube heat exchangers) or an air cooled condenser of the classic Rankine cycle [35].

The complete condensation of steam is produced at the steam absorber. In this device, the condensing temperature is increased above the saturation temperature of the pure steam for a given pressure in the steam absorber. In essence, if Ta is the condensing temperature in the steam absorber, and Tv is the water saturation temperature at the steam absorber pressure (Pa), being $Ta > Tv$ [36]. Ta value depends on the molality of the cooling reflux stream.

The outlet condensate (3) from the steam absorber is pumped to two circuits, one part (4) is directed to the deaerator where oxygen and other non-condensable gases are removed, while the other part acts as a cooling (2) reflux, passing through the air coolers, where condensation energy is eliminated by dry cooling.

The water from the deaerator outlet is pumped to the steam boiler and after that, the steam passes through the turbine, closing the cycle. The thermal energy of the boiler blowdowns (5) is recovered in an enthalpic recuperator by yielding its energy to the condensate stream that feeds the deaerator. The thermal [37] and chemical recovery of these purges is another fundamental advantage for the correct operation of the technology. There is a part of the boiler blowdowns (6) which is intermittently removed from the system to maintain chemical equilibrium in the cycle, due to the steam losses that exist at any given steam power generation cycle.

Figure 3. Steam absorber detail at the "Vetejar" biomass power plant.

2.2. Condensation differences between Rankine cycle and Hygroscopic cycle.

Figure 4 presents the different condensation designs between Rankine and Hygroscopic cycles.

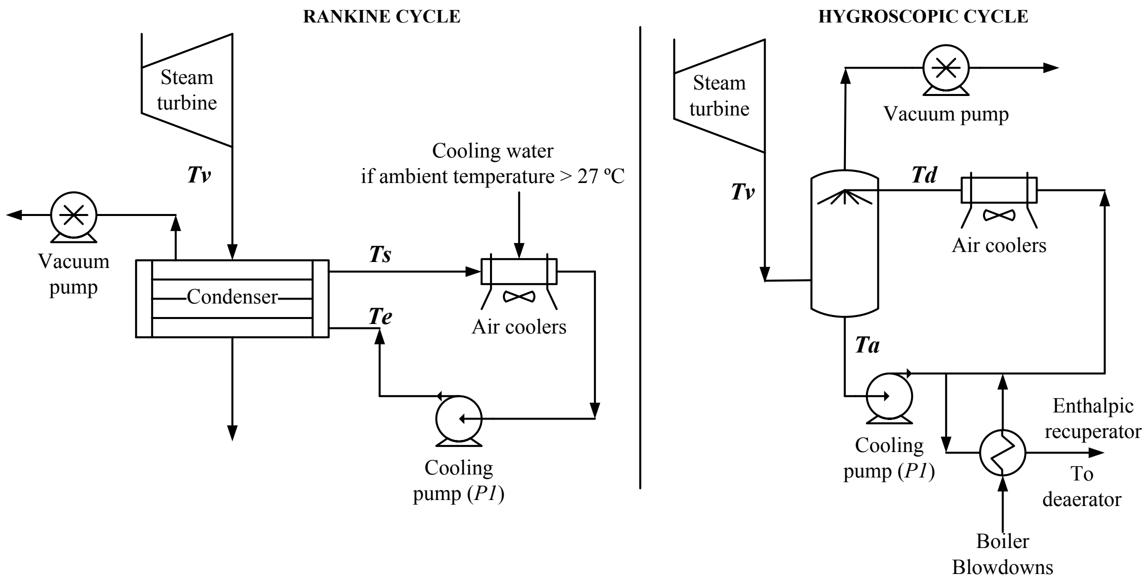

Figure 4. Steam condensation in Rankine cycle and Hygroscopic cycle.

As detailed in Figure 4, the following process conditions are fulfilled:

Tv is the condensing temperature of the steam at the outlet of the steam turbine (steam saturation temperature at the condensing pressure).

Ta is the temperature at the outlet of the steam absorber, which is higher than the condensing temperature (*Tv*). This difference in temperature depends on the molality of the cooling reflux current: The greater the molality, the greater the difference between *Ta* and *Tv*.

The cooling pump (*P1*) is the same for both Rankine cycle and HCT.

Te and *Ts* are the temperatures at the inlet and at the outlet of the cooling water of the condenser respectively.

Td is the temperature of the cooling water at the outlet of the air coolers (temperature at the inlet of the steam absorber).

The important parameter where the Hygroscopic cycle takes a clear advantage over the Rankine cycle is the temperature *Td*, which is higher than *Te* for the same condensing pressure at the turbine outlet, as will be shown in the next section below. For this reason, the cooling requirements in a Hygroscopic cycle are always easier to reach than in a traditional Rankine cycle.

3. RESULTS AND DISCUSSION

Ta-Tv is the value of the temperature difference between the saturation temperature of pure water and the condensing temperature at the steam absorber for a given pressure. For the "*Vetejar*" biomass power plant, the minimum difference necessary to assure that the condensation process does take place in the absorber has been found to be about 0.1ºC. It means that when $Ta - Tv < 0.1$, the molality of the steam is not enough to generate an stable heterogeneous hygroscopic nucleation of the water drops [38]. When $Ta - Tv > 0.1$, the condensation process is produced. The maximum value of $Ta - Tv$ obtained for the actual plant was 0.9 corresponding to the maximum steam molality.

$$Ta - Tv = \Delta T_1 \text{; with } 0.1 \leq \Delta T_1 \leq 0.9 \text{ (ºC)} \quad (1)$$

This temperature difference (ΔT_1), together with the cycle configuration allows the HCT to improve the refrigeration conditions and increase the electrical efficiency over a Rankine cycle, as it will be detailed below.

The main guarantees fulfilled to the existing installation when incorporating HCT is the ability to work with the lowest possible condensing pressure tolerated by the turbine, maintaining the highest electrical output when increasing the cooling temperature.

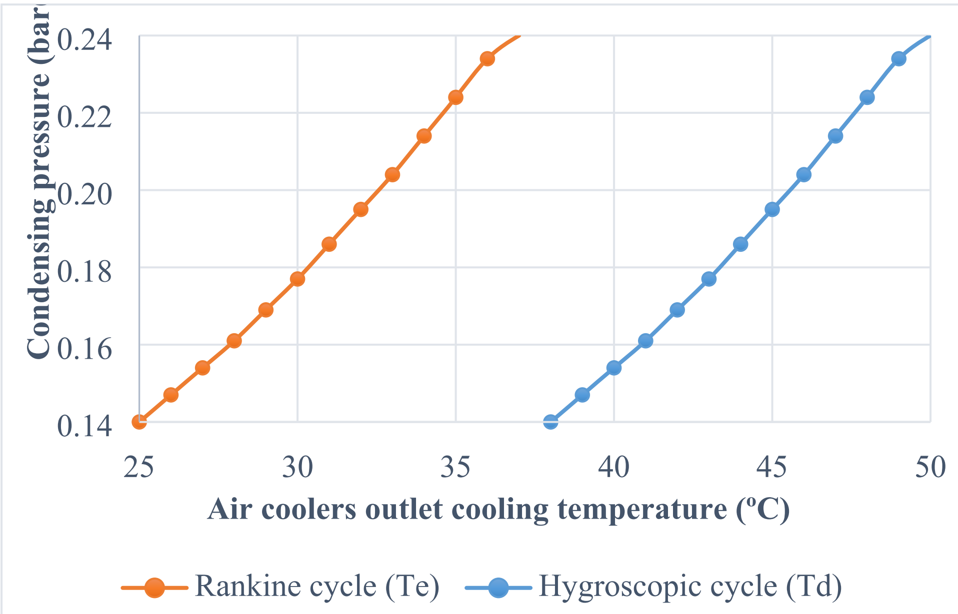

Figure 5. Condensing pressures vs. cooling temperatures.

The cooling temperature in both Hygroscopic cycle and Rankine cycle is the value of this variable at the outlet of the air coolers. *Te* in the Rankine cycle and *Td* in the HCT (Figure 4).

The difference in temperature between the inlet and the outlet to the air coolers of the liquid stream has remained the same in both cases, both using Rankine cycle (*Ts-Te*) and

Hygroscopic cycle (Ta-Td). This value has been kept between 10 and 14°C depending on the steam mass flow rate to be condensed (Equation 2):

$$Ts - Te = Ta - Td = \Delta T_2\text{; with } 10 \leq \Delta T_2 \leq 14\ (^{\circ}\mathrm{C}) \tag{2}$$

As it can be seen in Figure 5, for the same condensing pressure, Hygroscopic cycle works 13°C above the required cooling temperature in Rankine cycle (Equation 3).

$$Td - Te = 13^{\circ}\mathrm{C} \tag{3}$$

Thanks to this, the difference between the temperature of the water at the outlet of the air cooler and the ambient temperature becomes greater in a Hygroscopic cycle than a Rankine cycle (Td = Te + 13ºC), and consequently, the cooling by air convection taking place in the air coolers is more effective for HCT:

The cooling heat transfer rate (Qa) in air coolers is approximately the same for both Rankine and Higroscopic cycles. It can be calculated by Equation 4:

$$Qa = m_w \cdot C_w \cdot \Delta T_2 \tag{4}$$

being m_w the water mass flow rate and C_w the water specific heat capacity.

This cooling heat transfer rate must be provided by the air in the air cooler and it can be obtained by Equation 5:

$$Qa = m_a \cdot C_p \cdot \Delta T_3 \tag{5}$$

where m_a is the air mass flow rate, C_p is the average specific heat capacity of the air and ΔT_3 is the air temperature change through the air cooler.

From Equation 3 it is inferred that both ΔT_3 and C_p are greater for the Hygroscopic cycle than for the Rankine one and consequently, m_a is lower for HCT. It implies that the electric consumption of the air cooler fans becomes smaller for the new technology. The effect of the latter on the electrical efficiency will be discussed below.

The net electrical efficiency of the installation is obtained by Equation 6:

$$\eta = \frac{Wt - Ws}{Qi} \tag{6}$$

where:

η is the net electrical efficiency of the steam cycle.

Wt is the gross electrical power generated by the steam turbine.

Ws is the electrical power consumed by the different equipment of the steam cycle. Among them are air coolers, condensate pumps, boiler feed pumps, etc. The electric power consumed by the air coolers is lower for the HCT than for the Rankine cycle. The rest of the electric consumers (Figure 4) have the same electrical consumption in both Rankine and Hygroscopic cycles.

Qi is the thermal power required in the steam boiler. This value is the same in Rankine cycle as in Hygroscopic cycle.

The decrease in the electric power consumed by the air coolers for HCT (lower value of *Ws*) implies that the net electric efficiency is thereby increased (Equation 6). Also, the higher the temperature difference ΔT_1, the higher the air temperature change (ΔT_3), and also the HCT net electric efficiency increase is even greater, according to Equations 1 through 6.

In addition, the average monthly condensing pressure working with a Hygroscopic cycle is lower than that of the Rankine cycle. With the HCT it is possible to work with 100% steam mass flow rate for all ambient temperatures, with a maximum condensing pressure around 0.21 bar(a) for the maximum ambient temperature of 45ºC. With the Rankine cycle the cooling limit (maximum water consumption) is reached at an ambient temperature of 40 ºC (condensing pressure of 0.24 bar(a)), and the steam load must be reduced. The electrical power provided by the turbine increases as the condensing pressure decreases, with the consequent increase in monthly electrical energy production. The values registered at the power plant confirm that the Hygroscopic cycle contributes with an increase in the energy supplied to the electrical grid of 75 MWh/month on average.

The condensing average pressure of the Hygroscopic cycle was 0.186 bar(a). Figure 5 shows that for that pressure the required cooling temperature in Rankine cycle was 31 °C while for Hygroscopic cycle it was 44°C. Figures 6 and 7 compare the behavior of the air coolers for both technologies at the condensing pressure of 0.186 bar(a) for different ambient temperatures.

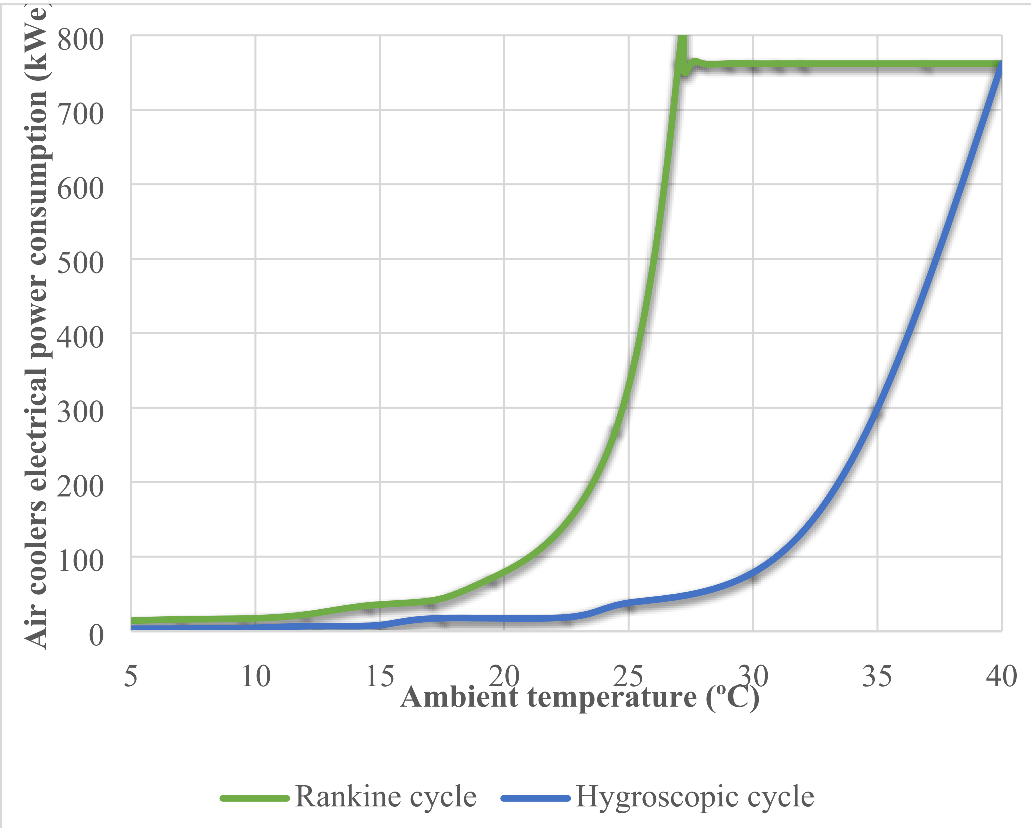

Figure 6. Air coolers electrical power consumption.

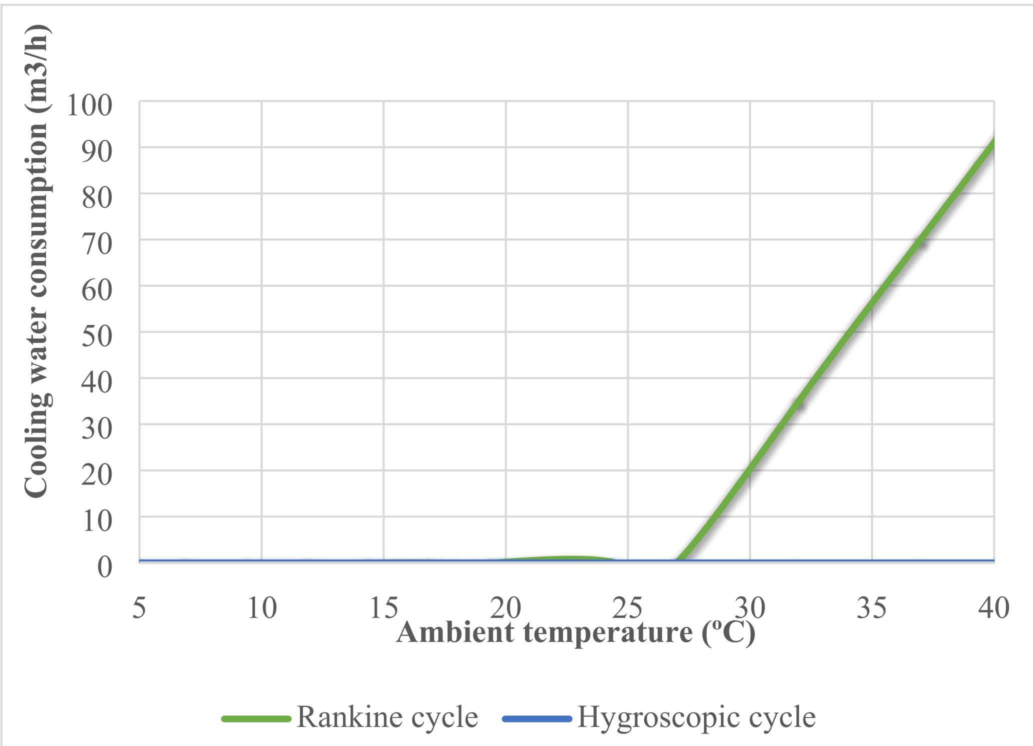

Figure 7. Air coolers cooling water consumption.

As shown in Figure 6, there is a significant lower electrical power consumption of air coolers with Hygroscopic cycle than Rankine cycle for different ambient temperatures. In addition, as shown in Figure 7, from 27 °C onwards, Rankine Cycle of the existing power plant start to consume cooling water, although with Hygroscopic Cycle ambient temperature can reach 40 °C without water consumption.

The following advantages are deduced by incorporating HCT to the existing installation:

- The annual average electrical power consumption of air coolers decreases from 320 kWe to 112 kWe. For 720 h/month of operation, approximately 150 MWh are saved while maintaining the same condensing pressure at the turbine outlet.
- The maximum peak consumption (all fans running) of 762 kWe in Rankine cycle occurs at an ambient temperature of 27 °C whereas this peak is reached at 40 °C for Hygroscopic cycle.
- Auto-consumptions in the Hygroscopic cycle will always be lower since air coolers will work at higher set point temperature for same condensing pressure.
- For the adiabatic spray system of air coolers the use of high quality water is necessary. It must be demineralized water. The demineralized water treatment plant has a rejection of 0.60 m^3 of water with dissolved salts to produce 1 m^3 of demineralized water. Regarding the cooling water consumption incorporated into the adiabatic cooling system of air coolers, the average annual consumption of cooling water with Rankine cycle was 19.1 m^3/h, with a maximum peak of 105.1 m^3/h at 42ºC. Compared to a null annual consumption in Hygroscopic cycle, it is deduced a demineralized annual water consumption saving of 143,250 m^3. As a result, the actual amount of raw water saved with HCT was 229,200 m^3 per year.
- Another problem solved when incorporating HCT is that Rankine cycle had a lower availability during summer peaks, when ambient temperature surpasses 35°C and also when cooling water consumption is limited by local regulations. In those cases, a significant increase of the condensing pressure is needed, with lower steam load. Occasionally the entire installation must shut down. HCT has eliminated such availability problems due to water scarcity, as reflected in previous results, and therefore, the mean annual condensing pressure is lower. In addition, HCT works at full steam load throughout the year, even at ambient temperatures of 45 ºC for which the condensing pressure is 0.21 bar(a) at full steam load. This value is still far from the maximum condensing pressure tolerable by the steam turbine of 0.24 bar(a).

- It should also be taken into account that the vacuum pumps incorporated with Hygroscopic cycle are slightly smaller than the current ones (with lower electrical consumption), more efficient, and without any cooling water consumption since they are in a closed loop circuit.
- In terms of net electrical efficiency and according to Equation 6 and the previous results, HCT contributes to *"Vetejar"* biomass power plant with an average annual increase of 2.5%.

Further to these savings, the power plant earns better availability of the installation, as well as an increase in the life span of air coolers. By avoiding the spraying of cooling water on the pipes and fins (adiabatic system), it decreases notably the corrosion phenomena they have suffered over the past years.

The improvements in the condensing and cooling conditions of a Hygroscopic cycle with respect to a traditional Rankine cycle, will allow the development of condensing turbines designed to work at lower condensing pressures for more hours per year, optimizing turbine isentropic efficiency at low pressures, with the objective of increasing the efficiency of the steam cycles, without using cooling water.

4. CONCLUSIONS

The incorporation of HCT to the 12.5-MWe "*Vetejar*" biomass plant has allowed the cooling temperature of air coolers to rise by 13°C for the same condensing pressure. It has made possible to reduce the electric consumption of air cooler fans, as well as to eliminate the use of cooling water used by the adiabatic system thereof, thus increasing the life span of such equipment by reducing the corrosion of copper tubes and aluminum fins.

The electrical performance obtained by the Hygroscopic cycle is always higher than the initial Rankine cycle installed. This allows the installation to operate with two alternative modes. The first one consists on obtaining lower condensing pressures for the same cooling temperature, and therefore a better gross electric performance is achieved. The second alternative, currently used in the studied power plant, keeps the same condensing pressure as the initial Rankine cycle. In this case, the cooling temperature is increased, obtaining improvements in net electrical efficiency, with savings of 150 MWh/month in electric energy consumed by the air coolers, 229,200 m^3 in cooling water consumed annually by the adiabatic cooling system thereof. Besides, an additional monthly electrical energy of 75 MWh is discharged to the grid due to the higher availability of the power plant. It is also possible to work at lower condensing pressures at full steam load for more hours per year, increasing the power output. In terms of net electrical efficiency, HCT contributes with an annual average increase of 2.5%.

Therefore, the improvements achieved by the Hygroscopic Cycle have made the installation much more efficient, safe (less shut-down and start-up operations), cost-effective, and without the need to expend cooling water.

This opens a new field of improvement in steam cycles with the incorporation of Hygroscopic cycle technology, whose next step will be to reach higher power thermoelectric power plants. Despite the fact that the results obtained for this particular power plant are quite good, the implementation of this technology in other power plants with greater turbines or working at supercritical conditions must be analyzed for each installation. Based on the present study, the expected results for the application of HCT to different industrial turbines will hopefully allow to obtain a better performance of the cycle.

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