Experimental study on the influence of the saline concentration in the electrical performance of a Hygroscopic cycle

Francisco J. Rubio-Serrano[a] , Fernando Soto-Pérez[a], Antonio J. Gutiérrez-Trashorras[b,*]

[a] IMASA, Ingeniería y Proyectos, S.A. Carpinteros 12. 28670 Villaviciosa de Odón (Madrid) Spain

[b] Energy Department, Escuela Politécnica de Ingeniería. Edificio de Energía. Universidad de Oviedo. 33203 Campus de Viesques. Gijón (Asturias) Spain

Abstract

The Hygroscopic cycle is a novel proprietary power cycle characterized by working with hygroscopic compounds which optimize the condensation of the turbine output steam in a steam absorber. This technology can be incorporated in any power plant that uses a Rankine cycle, obtaining higher electrical efficiency without limiting the cold sink temperature and without cooling water consumption. The novelty of this article is that Hygroscopic cycle is experimentally investigated in a test power plant with high concentrations of lithium bromide solution in water in the cooling reflux to analyze the effect on condensing temperature, condensing pressure, power output and efficiency. Mass concentration of lithium bromide in the cooling reflux stream ranges from 45 to 65%. The increase in salt concentration at the cooling reflux stream allows the condensing temperatures to be significantly increased by more than 15°C in a Hygroscopic cycle with respect to a Rankine cycle. Results also show that it is possible to decrease the turbine outlet condensing pressures for the same condensing temperature. Thereby, as mass concentration of lithium bromide is increased the gross electric power output increases with reference to a Rankine cycle for the same condensing temperature. The minimum increments in net electric power output and electrical efficiency are 7.6% and 2.6% respectively.

Keywords: Rankine cycle, steam absorber, lithium bromide, electrical efficiency, condensation nuclei.

*Corresponding author. Energy Department, Escuela Politécnica de Ingeniería. Edificio de Energía. Universidad de Oviedo. 33203 Campus de Viesques. Gijón (Asturias) Spain. Tel.: +34 985 18 23 69.
E-mail address: gutierrezantonio@uniovi.es.

1. INTRODUCTION

Since the recent energy crisis, industrial stakeholders and researchers have looked for better ways to manage energy, mainly by increasing energy systems efficiency. In this context, interest for improving thermoelectric generators has increased significantly. Rankine cycle is the basic thermodynamic cycle used in thermoelectric power plants for electricity generation. In this article, a new cycle improving Rankine performance is experimentally investigated. Also, its advantages and great potential for current and future power plants are explained.

Rankine cycle [1] is a thermodynamic cycle whose purpose is the transformation of heat into work. As it is known in the energy industry, its effectiveness is limited by the thermodynamic efficiency of a Carnot cycle operating between two heat reservoirs. The main advantage of this cycle is its industrial maturity, coming from a long and continuous development, and its high degree of applicability in many different processes. Improvements have been achieved mainly by increasing the temperature difference between the cold and the hot sink, resulting from the evolution of materials to be able to sustain increasingly restrictive conditions, up to supercritical water conditions. Also, due to the improvement of thermal [2] and mechanical designs, condensers with very low pressure at the exit of the turbine, down to or below 0.1 bar, have been implemented. As a result, electrical efficiency of the cycle increases.

Rankine cycle efficiency has been deeply studied for many decades [3,4]. Most of the methods used to improve thermal efficiency of Rankine cycles are based on reducing irreversibilities. It also avoids for the maximum humidity in the turbine steam to reach lower values than 10% [5]. A thermodynamic analysis of regenerative-reheat Rankine cycle power plants [6] shows that the feed water heating and reheat in addition to regeneration provide an efficiency enhancement up to 14%. Supercritical Rankine cycle using zeotropic mixture working fluids improve 10-30% thermal efficiencies over the organic Rankine cycle (OCR)

[7]. An exergy analysis for a 650 MW thermal power plant has been developed in [8]. The relationship between power plant exergy and thermal efficiencies was presented. Also, the effect of the decreasing condenser pressure and increasing superheating steam temperature inlet to both high and Intermediate Pressure Turbine was studied.

Organic Rankine cycle (ORC), Goswami cycle and Kalina cycle are the major cycles developed for the conversion of low-grade heat into electricity [9]. Most of current investigations about Rankine cycle focus on ORC [10]. It uses working fluids with low boiling points in order to recover heat from a low temperature heat source. The effect of flow losses in the condenser on the performance of ORC was studied in [11]. The results obtained show that the relationships of total irreversibility, net work output, thermal efficiency and exergy efficiency between the practical cycle and ideal cycle are linear. Some authors present other ways to enhance the efficiency of an ORC by using absorption systems. Most common absorption types are based on ammonia-water (NH_3-H_2O) solution and a water-lithium bromide (H_2O-LiBr) solution. In [12], a method to enhance the ORC with absorption systems is evaluated. The ORC condenser was replaced by an absorption unit. That system simultaneously generates power and cooling energies at the average energy and exergy efficiencies of 20.61% and 21.54%, respectively. A comparative investigation on thermo-economic performance between ORC and LiBr absorption refrigerating cycle in waste heat recovery was presented in [13]. Results show that, the thermo-economic performance of LiBr absorption refrigerating cycle and ORC using zeotropic mixture as working fluid are better than that of ORC using pure working fluid at any heat source temperature. The ORC technology is limited by the maximum temperature of the working fluids used. At present, the maximum operating temperature is about 300 °C. Electrical efficiency can reach values above 30%. In combined heat and power (CHP) applications, the very high temperature ORC systems could be an effective and profitable solution. [14] presents the technical and industrial development on High

Temperature ORC systems, potential market development and a technology comparison to other generation technologies. Nonetheless, currently ORC practical use is limited to low power generation [15].

Kalina cycle is a thermodynamic power cycle using an ammonia–water mixture as the working fluid. It marked a significant improvement in thermal power plant design since the introduction of the Rankine cycle in the mid-1800s and can be considered as a competitor of the OCR. [16] reviews the research on the Kalina cycle, including the description of the cycle and the comparison to Rankine. The design of Kalina provides an additional degree of freedom in the composition of the boiling mixture and a much higher overall efficiency than the OCR. Simple Kalina cycle is composed of several devices: boiler, turbine, distiller, separator, 2 reheaters, absorber, condensate pump, throttle valve, condenser, boiler feed pump and feed water heater. It needs cooling water for refrigeration. The application of the Kalina cycle is restricted to medium–low temperatures heat sources (maximum temperatures of 300–400 °C).

Rankine-Kalina combined cycle [17] produces higher power output and is more efficient than a Rankine steam cycle, because of the reduction of losses in the turbine exhaust and in the condenser. A recent study from [18] shows that the effect of different combinations of the ammonia-water Rankine power cycle and the ammonia-water absorption refrigeration cycle are very effective on the thermodynamic and exergoeconomic performance of a cogeneration cycle.

Goswami cycle uses binary mixture to produce both power and refrigeration [19]. A mixture of ammonia and water is pumped from an absorber to high pressure. It is then split into two streams which, after recovering heat, are mixed and enter the desorber. The mixture is partially boiled in the desorber to produce a vapor rich in ammonia and a hot weak-in-ammonia liquid solution. A rectifier increases the concentration of ammonia in the vapor from the desorber, by partially condensing water out of it. Goswami and Xu [20] conducted a parametric analysis to study the effect of the cycle parameters on the performance of the cycle. Application of low heat-source temperatures below 200 °C is one of the characteristics of this cycle. A combined Rankine–Goswami cycle (RGC) is proposed and a thermodynamic analysis is conducted in [21]. The Goswami cycle, as a bottoming cycle, uses ammonia–water mixture as the working fluid and produces power and refrigeration. The results indicate that the proposed RGC provide a difference in net power output between 15.7% and 42.3% for condenser pressures between 1 and 9 bars.

Recently, a new proprietary cycle which provides greater efficiency than Rankine Cycle and significantly reduces water consumption for cooling was developed by the researcher Rubio-Serrano [22] and co-workers. That technology was named by those researchers as Hygroscopic Cycle Technology (HCT) [23]. HCT has been in the state of the art since 2010 as "Rankine Cycle with absorption stage using hygroscopic compounds" [24,25]. It is a novel power cycle, similar to the Rankine cycle, characterized by working with hygroscopic compounds, which optimize condensation of the turbine exhaust steam. Such compounds [26] must have the following characteristics: they must be highly hygroscopic compounds [27], which attract water as vapor or liquid from the environment; they should be less volatile than water (vapor pressure less than water) and easily separable, so that the retention is reversible, and the vapor can be readily desorbed [28]; they must be chemically stable at the working pressures and temperatures of the cycle; they must be non-toxic and non-flammable compounds. Consequently, Hygroscopic Cycle incorporates the physical and chemical principles of absorption [29] machines to give greater performance and better cooling conditions than Rankine cycle. HCT has also many advantages respect to both Kalina and Goswami cycles. Those advantages are that HCT is not limited to conversion of low-grade heat into electricity and it is potentially applicable to any range of power generation. Besides, binary mixture does not use neither an external heat source nor a desorber to separate the steam from the other fluid. In HCT, only one absorber is used, in which the steam is directly condensed by absorption due to the different concentration of hygroscopic compounds between the stream inlets [30]. The layout of HCT is much simpler than those of Kalina and Goswamy since the number of components is considerably fewer. So far, only a few investigations have been published about HCT because of its recent development. The installation of the first test plant of the Hygroscopic cycle was finished in 2015 (Figure 1). This plant was placed in Gijón (Spain) and is owned by IMASA, INGENIERÍA Y PROYECTOS S.A [31]. That plant was used by the authors of this paper for the development of HCT [30] and for the investigation conducted in this article. The vital elements of HCT are the absorber and the cooling system associated. After the turbine, the steam is condensed by means of the chemical process of absorption inside the absorber. The cooling reflux stream provided by the cooling system is also introduced in the absorber. That stream is a solution of hygroscopic compounds in water and comes into contact with the pure steam in the absorber. It produces the steam condensation by absorption. As a result, two important advantages can be achieved in a Hygroscopic cycle over a traditional Rankine cycle:

1. Decrease of the condensing pressure for a given condensing temperature. Consequently, higher electric power provided by the turbine and higher electrical efficiency of the installation are obtained.
2. Increase of the condensing temperature for a given condensing pressure. As a result, cooling temperate is also increased. It allows dissipation of the energy of condensation in dry mode (air-cooler), instead of a cooling tower, with the subsequent saving of water [32], tower purges, plumes, and associated operation and maintenance costs. This water saving is one of the main advantages of using this technology, given the shortage of water that mankind will have in the future, and therefore the high cost that will be associated to it.

In HCT, dry coolers are used to dissipate the heat of condensation (cooling system). It is composed of heat exchangers in which the hot fluid is cooled by an air stream driven by fans of high electrical efficiency. The speed of the fans is controlled according to the ambient temperature [33].

Figure 1. Hygroscopic cycle test plant with the steam absorber in first place.

The benefits of incorporating the innovative technology of the Hygroscopic cycle to an existing biomass power plant have been published by Rubio-Serrano et al. [30]. In that paper, the first world reference at industrial scale that uses this technology is exposed. It is a 12.5-MW biomass "Vetejar" power plant located in Palenciana (Córdoba-Spain). The boiler blow-downs are used as hygroscopic compounds in order to induce the condensation of the turbine outlet exhaust steam in the steam absorber. In this device, the condensing temperature is increased above the saturation temperature of the pure steam for a given pressure. As a result of the condensing temperature increase and the cycle configuration, HCT improves refrigeration conditions and increases the electrical efficiency over a Rankine cycle. The new technology allows the plant to refrigerate at high ambient temperatures, increases the net electrical efficiency of the plant and its efficiency. Also, the cooling tower was removed, avoiding cooling water consumption. The actual amount of raw water saved in that plant with HCT is 229,200 m^3 per year. The values registered at the power plant confirm that the Hygroscopic cycle contributes with an increase in the energy supplied the electrical grid of 75 MWh/month on average. In terms of net electrical efficiency, HCT contributes to “Vetejar” biomass power plant with an average annual increase of 2.5%.

Due to its characteristics, HCT can replace a Rankine cycle for any electric power range in new or existing power plants [25] such as combined cycles, biomass power plants thermoelectric power plants, thermosolar power plants and nuclear power plants; as well as CHP systems.

In the literature, the relationship between the different parameters governing the HCT have not been thoroughly studied. The relationship between condensing pressure and condensing temperature in the absorber is vital for the understanding and effective functioning of the cycle. Absorption process determines that the condensing pressure in the absorber of HCT is lower than the pressure of the pure steam in a Rankine cycle for a given condensing temperature. Consequently, both net electric power and electrical efficiency of the plant are increased. That relationship between the variables above mentioned has been only studied for the case of the “Vetejar” power plant [30], in which the concentration hygroscopic compounds is very low (less than 1%, provided by the steam boiler blow-downs). There are not any other studies relating condensing temperature and pressure in the absorber for higher concentrations of hygroscopic compounds. From a practical point of view, the cooling temperate is the variable that can be adjusted, basically by means of the fans of the dry coolers. Cooling temperature is really the temperature set point and it is directly related to the condensing temperature. Condensing temperature can be fixed by setting the cooling temperature and the mass concentration of hygroscopic compounds.

This article deals with decreasing the condensing pressure at the end of the expansion in a power cycle. This point is of vital importance in a steam cycle, since the lesser condensing pressure is achieved, the better the electrical performance of the steam cycle.

The novelty of the present work is that instead of only using the steam boiler blow-downs (as in "Vetejar" power plant), HCT is analyzed with a different hygroscopic compound and at higher concentrations, in order to increase the effect of lowering the condensing pressure. Therefore, it can be quantified the increase of both power production and efficiency of the cycle, depending on the compounds used and its concentration. The hygroscopic compound selected was lithium bromide (LiBr) which fulfills the characteristics needed for the cycle and that were exposed in the introduction. LiBr is currently used in refrigeration systems by absorption [29, 34] for cold production and it is a highly hygroscopic soluble salt at all thermodynamic states of HCT. LiBr exhibits an increase of solubility in water as the temperature of the solution is increased [35]. Also, the effect of increasing LiBr concentration on the electrical power production of the turbine and the efficiency of the cycle is analyzed in this paper.

The main objective of this paper is to experimentally study the influence of the concentration of lithium bromide of the cooling reflux current on the condensing temperature and on the electrical performance of the hygroscopic cycle. The effects of providing a high increment of the LiBr concentration of the reflux cooling stream and therefore a higher reduction of the condensing pressure with respect to that of a Rankine cycle, increasing power production and efficiency, will be the main goal of this article.

2. MATERIALS AND METHODS

2.1 Hygroscopic cycle test plant

Experimental values presented in this article have been obtained from the previously mentioned test plant of the Hygroscopic cycle (Figure 1) [23]. The test plant is located at Gijon

– Spain (43°32′N 5°42′W) and it is the first worldwide test plant replicating the HCT. The plant comprises all the equipment and materials necessary to investigate HCT. That equipment is available at industrial scale as well. The design, supervision and start-up of the test plant (Figure 1) was carried out by the Energy Division of the company IMASA, INGENIERÍA Y PROYECTOS, S.A. [34]. Figure 2 shows the arrangement of the devices included in the test plant. HCT comprises the following main equipment: steam turbine [36], steam absorber [37], condensate pump [38], feed water pump [39], vacuum pump [40], enthalpic recuperator [41], thermal deaerator [42], steam boiler [43] and dry coolers [44]. The elements of the test plant are the same, except for the steam turbine that is replaced by an expansion valve. The test plant reproduces all the processes taking place in an actual HCT, but the turbine is simulated by means of the expansion valve and a Supervisory Control and Data Acquisition (SCADA) system. Figure 3 presents the flow diagram of the Hygroscopic cycle test plant, including the different processes, equipment and fluid streams involved, as well as the turbine equivalence (valve and SCADA).

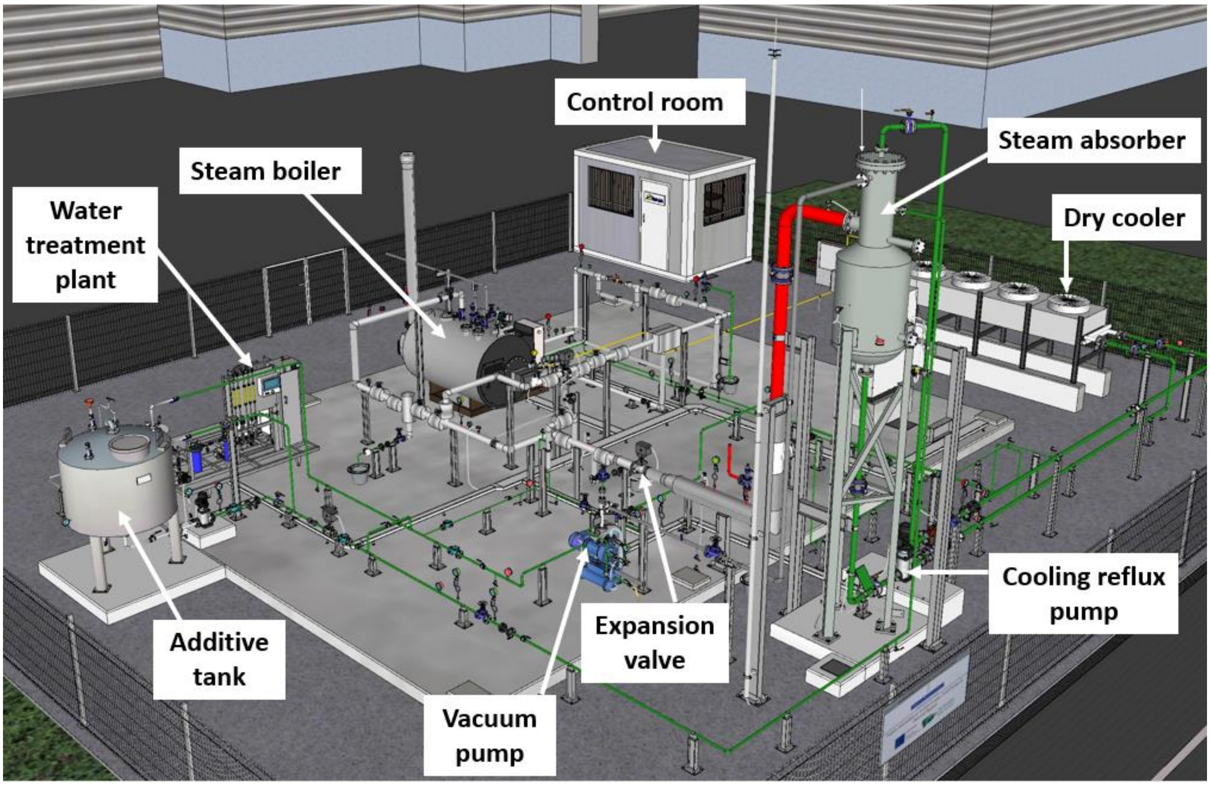

Figure 2. Arrangement of the Hygroscopic cycle test plant.

The different streams are shown in Figure 3. Stream (1) corresponds to the live steam produced by the boiler. The turbine exhaust steam form is numbered as stream (2). Streams (1) and (2) contain only water. The rest of the streams contain LiBr solutions in water. The cooling reflux is reflected in stream (3). Cooling temperature is measured at that stream. The condensate is shown as Stream (4). Streams (5) and (6) are the boiler feed water currents before and after the deaerator respectively. The boiler blow-downs are reflected in stream (7). Intermittent purges are shown as stream (8). Make-up water with additives is reflected in stream (9). Condensing pressure and temperature data are taken directly from pressure and temperature sensors located in the steam absorber.

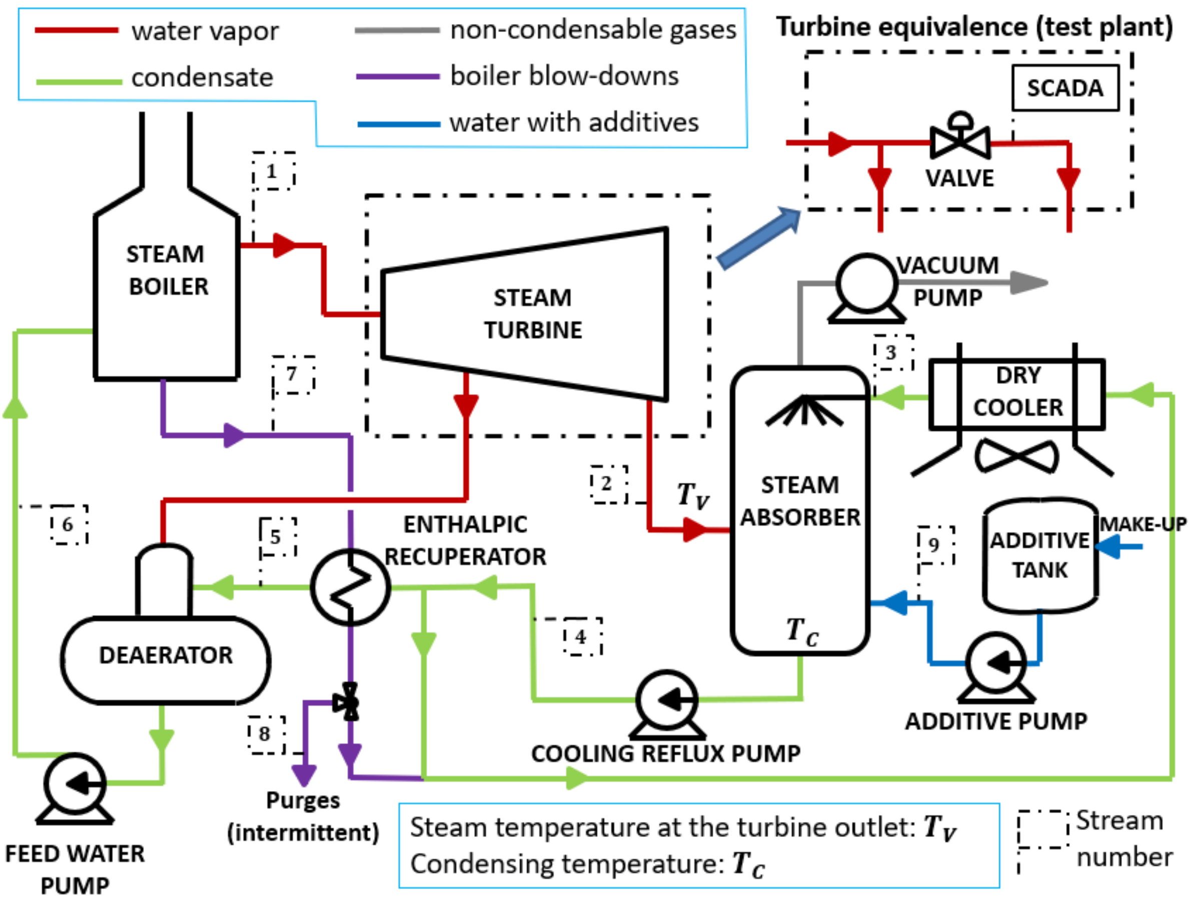

Figure 3. Hygroscopic cycle test plant flow diagram.

In this study, the mass flow rate of live steam was 100 kg/h. According to the process diagram shown in Figure 3, the superheated steam (1) produced in the boiler (with natural gas as fuel) expands in the expansion valve. The boiler is a pyro-tubular 100-kW boiler with steam generation capacity of 110 kg/h at 13 barg and maximum temperature of 200ºC. A high efficiency droplet separator is located at the outlet of the boiler in order to minimize the dragging of salts into the turbine. The expansion valve simulates the conditions of exhaust steam at the exit of a steam turbine. Experimental thermodynamic data at the outlet of the isenthalpic expansion are registered in a PLC [45]. The SCADA system [46] gathers, controls and supervises all data and it is programmed to simulate and calculate the instantaneous electric power of a steam turbine. In the simulation, live steam conditions are 60 bar(a) and 500 ºC (at turbine inlet). The simulated turbine is able to produce 38 kWe of power output at the scale of the plant. The exhaust steam [47] from the expansion valve (2) is directed to the steam absorber where it is brought into contact with a liquid stream of condensate, which acts as a cooling reflux (3). The liquid condensate stream is rich in hygroscopic compounds and has a higher salt concentration than the steam (2) since the selected hygroscopic compounds are not volatile. In figure 3, *Tc* denotes the condensing temperature of the vapor in the steam absorber and *Tv* designates the saturation temperature [48] of exhaust steam. In the steam absorber, complete condensation of the steam occurs by absorption, releasing the heat of dilution [49] that is defined as the heat exchanged with the medium when an additional amount of solvent is added to a solution. As a result, *Tc* is always greater than *Tv*. The condensing pressure has the same value at the turbine outlet and in the steam absorber. Air and other non-condensing gases are extracted from the steam absorber by the vacuum pump. The outlet condensate (4) of the steam absorber is pumped to two circuits, one part (5) is directed to the thermal deaerator unit where oxygen and other non-condensable gases are removed, and another part is recirculated as cooling reflux (3). It flows through an air cooler where the condensing energy is removed by dry cooling. The condensate (6) at the outlet of the deaerator is pumped (by the feed water pump) to the steam boiler. A high efficiency droplet separator at the exit of the boiler avoids dragging of salts towards the turbine. Thermal energy of the boiler blow-down (7) is recuperated in the enthalpic recuperator (a closed heat exchanger) by yielding its energy to the condensate stream that feeds the thermal degassing unit (deaerator). Thermal and chemical recovery of these purges is of vital importance for the correct operation and net electrical performance achieved in the technology. The concentration of these boiler purges is significantly higher than the obtained in a Rankine cycle. Part of the boiler bleed (8) is removed from the system intermittently to maintain chemical equilibrium in the cycle, due to the steam losses that exist in any cycle of this type. Water treatment plant (Figure 2) converts the network water into osmotized water [50], demineralized, or a mixture of them. Quality control of the water produced is carried out on that equipment. The mixture of treated water (make-up), chemical additivation to the cycle, and the dissolution of hygroscopic compounds in water is conducted in the additive tank (2-m^3 atmospheric tank) shown in Figures 2 and 3. These chemicals consists of a mixture of amines [51,52]. It avoids the formation of scale and protects all metallurgy against corrosion due to oxygen, other dissolved gases and the hygroscopic salts incorporated in the technology.

Hygroscopic compounds consist mainly of the selected hygroscopic salt (LiBr) and in a much lower concentration of dissolved solids, silica, alkalinity, iron, and the mentioned chemical additives. The mass concentrations of LiBr in water used in this article, ranges between 45 and 65% in the cooling reflux. For concentrations lower than 45% results barely differ respect to the obtained with the boiler blow-downs of the Rankine cycle because the heat of dilution [49] is very low. 65% is the maximum solubility of LiBr in water for the working temperature range in the cooling reflux of the test plant [35]. The behavior of those solutions is quite different from that of ideal diluted solutions that follow the colligative properties of water [53]. Raoult's law is of particular interest for these purposes [54]. According to that law, the boiling point of water and the decrease in the vapor pressure are directly proportional to the concentration of solute (LiBr). In the present study, since these are actual solutions and at high concentrations [55], the increase in boiling point is much higher because the decrease in vapor pressure do not follow a linear but a polynomial tendency as the hygroscopic compound concentration increases [53].

2.2 Steam absorber

The operation of the steam absorber, shown in Figures 2 and 3, and the importance of the salt concentration in the cooling reflux stream, will now be described. The steam absorber is similar to a direct contact condenser [56], where spray nozzles are located at the top, which generate droplets of liquid from the reflux stream of cooling. The main factors influencing the droplet diameter are flow rate, pressure and nozzle type. Generally, an increase of the flow at constant pressure causes an increase in the size of the drops. By increasing the pressure, the diameter of the drops is reduced, increasing the spray angle. The greater the mass concentration of dissolved lithium bromide in the cooling reflux, the greater the hygroscopic content of the microdroplets. These compounds are always less volatile than water (lower vapor pressure) with a strong affinity for it. Microdroplets act as condensation nuclei, increasingly stable as the concentration of hygroscopic compounds increases [57]. The behavior of the hygroscopic nuclei in contact with water vapor establishes that since the vapor pressure for a given temperature decreases as the salt concentration in the nuclei increases, the vapor is condensed in these microdrops as the vapor pressure of the solution is lower than that of the pure water, forming larger droplets which further favor vapor condensation. In addition, by adding molecules or ions to a pure solvent, in this case water vapor, the temperature at which it boils is higher. For this reason, the increase in lithium bromide concentration in water (coming from the cooling reflux) in the steam absorber causes an increase in the actual condensing temperature. The increase in the stability of the condensation nuclei and the preference of the condensation of steam on these nuclei instead of in others has direct relation with the osmotic pressure [58], another important colligative property of the water. Increasing the mass concentration increases the osmotic pressure of the system, and therefore, the affinity of the water vapor towards these high concentration microdroplets through absorption. Therefore, the Hygroscopic cycle shows an efficient condensation system without the need to increase the stability of the drops with subcooling. Furthermore, condensing pressure can be lowered by increasing the mass concertation of LiBr in the cooling reflux stream for a fixed condensing temperature.

3. RESULTS AND DISCUSSION

Figure 4 shows the results obtained in the test plant for different concentrations of the LiBr solution in water. In that Figure, condensing pressure (*Pc*) in the absorber and condensing temperature (*Tc*) at the exit of the absorber are experimentally correlated for different mass concentrations of LiBr in the cooling reflux of HCT and for pure water (0%).

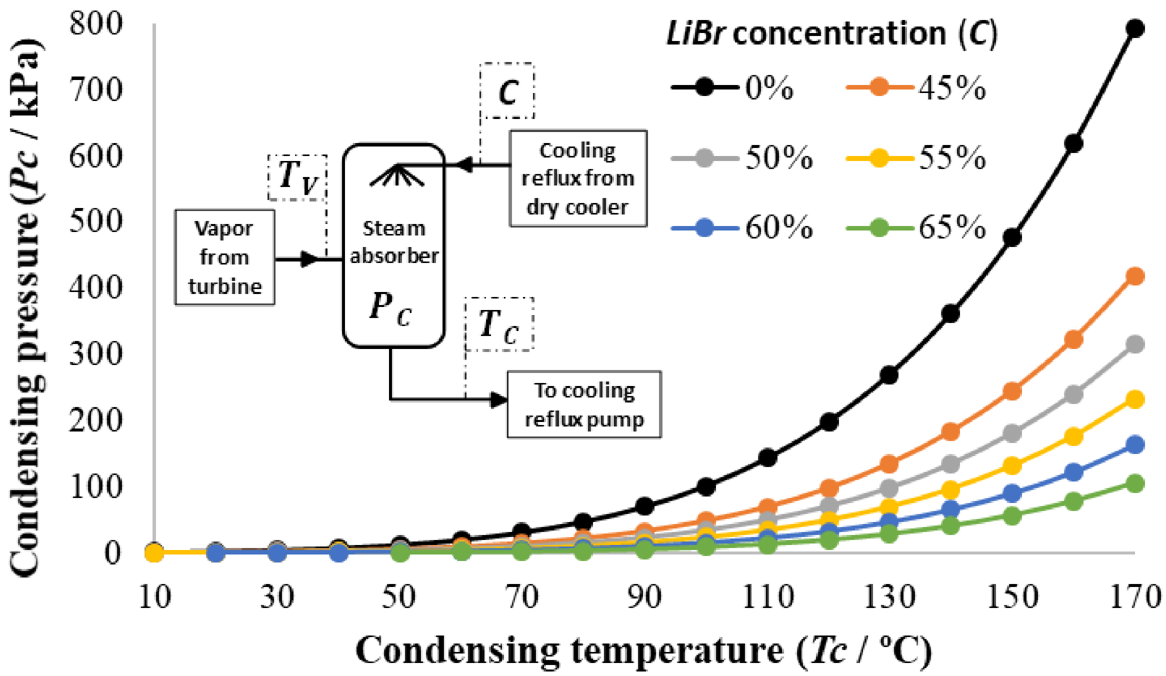

Figure 4. Condensing pressure vs. condensing temperature for different mass concentrations (%) of the LiBr solution in water in the cooling reflux.

According to the test plant experimental results, the mass concentration of LiBr in the cooling reflux stream has a very significant the influence on the relationship between condensing pressures and temperatures required by the HCT. They are also different from the relationship for pure water which corresponds to Rankine cycle. Figure 4 shows that as the mass concentration of the LiBr solution in water at the cooling reflux stream (stream 3-Figure 3) increases, the condensing pressures measured at the absorber are lower for a given temperature. Accordingly, the incorporation of the hygroscopic LiBr salt, being a non-volatile salt at working temperatures, contributes to decrease the vapor pressure of the system, with a stronger contribution, the higher the concentration thereof. Furthermore, the difference between the condensing pressure of pure water (0% concentration) and the rest of saline solutions increases as temperatures increase.

In Figure 3, the outlet steam from the expansion valve (stream 2), upon contact in the steam absorber with the cooling reflux (stream 3), condenses at a temperature greater than the saturation temperature found in the steam tables for this pressure, and this is the great advantage and novelty using the present technology in a steam cycle. According to Figure 4, condensing temperature increases by more than 15°C respect to the steam saturation temperature for a given condensing pressure. The cold sink temperatures (atmospheric, or dry bulb temperature most commonly used in industry), which limit the condensing pressure of the turbine outlet steam in a traditional Rankine cycle, are not limited in a Hygroscopic cycle given the significant increase in the actual condensing temperature that the steam undergoes in the steam absorber.

It was previously commented in the introduction and justified in section 2.2 that there are two operating options or a mixture of both in a Hygroscopic cycle. The first operating option consists on maintaining the condensing temperature while the condensing pressure is reduced in the absorber. Consequently, the Hygroscopic cycle manages to increase the power output of the steam turbine and the electrical efficiency of the cycle. Figure 5 details this result with an example. The practical method to maintain the condensing temperature is by setting the cooling temperature and the mass concentration of hygroscopic compounds. For an optimized design of HCT, the temperature difference between condensing temperature and cooling temperature ranges from 7 to 14°C. Figure 5 shows that for a condensing temperature of 45°C and a cooling temperature of 35°C, the condensing pressure of the steam in a Rankine cycle is 12.4 kPa(a) against 4.24 kPa(a) in a Hygroscopic cycle, with a mass concentration of LiBr in water of 45% at the cooling reflux stream.

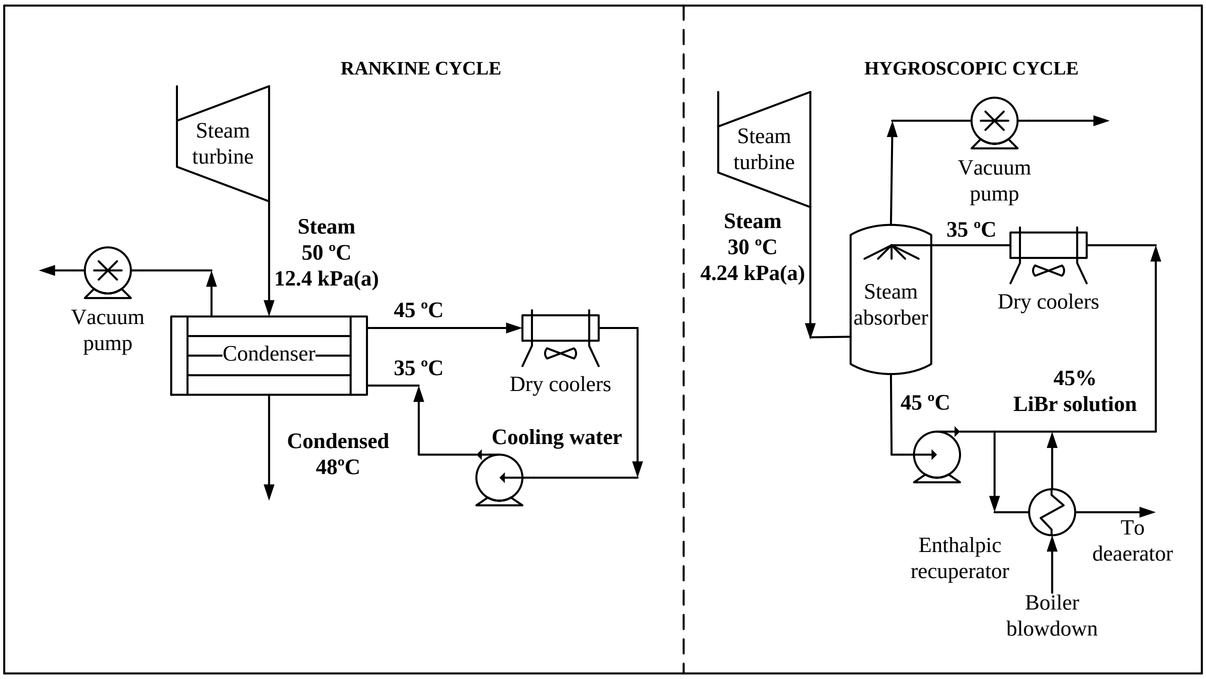

Figure 5. Comparison between condensing pressure for a Hygroscopic cycle with respect to a Rankine cycle for the same cooling temperature.

The second operating option consist on keeping the same condensing pressure in the absorber, while increasing both condensing and cooling temperatures, thereby improving the cooling of the system. Figure 6 details the results obtained on second operating option with an example. It shows that for a condensing pressure of 7 kPa(a), the required cooling temperature in a Rankine cycle is 24 °C, while in the Hygroscopic cycle is 45 °C, with a mass concentration of bromide of lithium in water of 45% in the cooling reflux stream. Also condensing temperatures are shown in Figure 6. The Rankine cycle would require a cooling tower, with a significant consumption of cooling water, as opposed to a high efficiency electric dry cooler in the case of a Hygroscopic cycle. The values detailed in Figure 6 could be obtained at an ambient temperature (cold sink) of 40 ºC. Therefore, it is confirmed that the Hygroscopic cycle is not as limited as a Rankine cycle by the cold reservoir temperature.

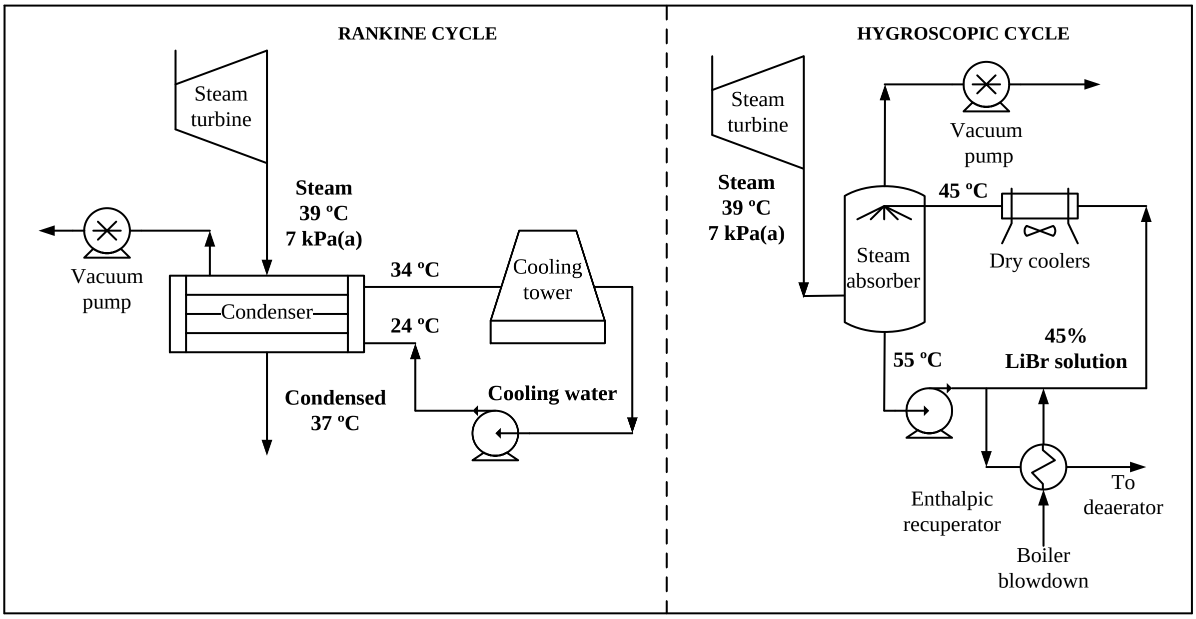

Figure 6. Comparison between cooling temperature for a Hygroscopic cycle with respect to a Rankine cycle for the same condensing pressure.

The steam after the high efficiency droplet separator located at the outlet of the boiler is practically pure, with the required quality for turbines, since LiBr is a non-volatile salt for pressure and temperature conditions in the boiler. In addition, given the increase in boiling point of the LiBr solution inside the boiler due to colligative properties, pure vapor is always superheated at the inlet of the turbine. In practice, the only implication is that the section of the steam superheater in the boiler is significantly reduced or it is not even necessary in HCT.

Figures 7 and 8 show the electric power output and the increment in gross electric power output respect to Rankine, from the experimental data obtained in the HCT test plant with the first operating mode. The inputs for the simulated steam turbine and the SCADA system were:

- Live steam at 60 bar(a) and 500 ºC was considered at the inlet of the simulated turbine.
- The exhaust pressure at the outlet of the simulated turbine was the pressure measured at the outlet of the expansion valve of the Hygroscopic cycle test plant.

- Turbine efficiencies considered: 82% isentropic efficiency and 97% electrical efficiency.
- The experimentally measured mass flow rate of live steam in the Hygroscopic cycle test plant that was 100 kg/h.

Condensing temperatures and pressures experimentally measured at the steam absorber and concentrations of the cooling reflux in the Hygroscopic cycle test plant were also used for calculations.

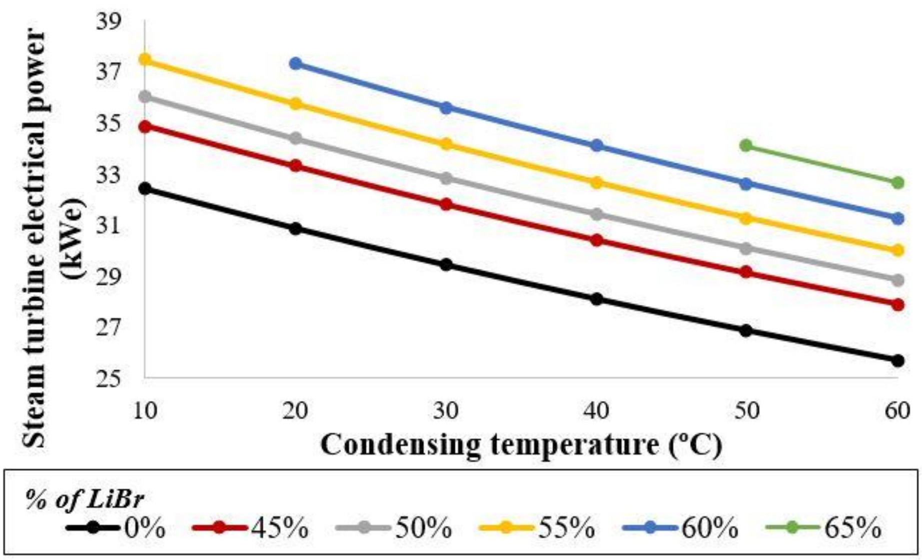

Figure 7. Electric power obtained in the steam turbine for condensing temperatures between 10 and 60°C and different mass concentrations (%) of LiBr solution in water.

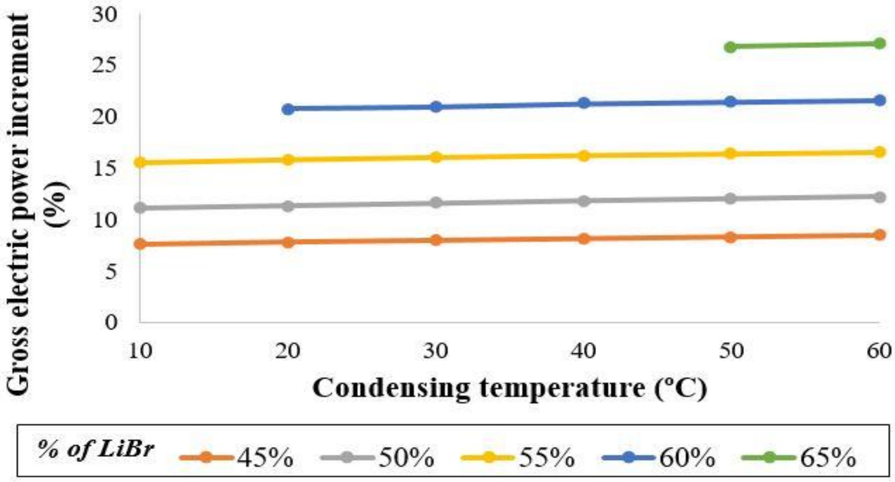

Figure 8. Increment in gross electric power output at condensing temperatures between 10 and 60°C and different mass concentrations (%) of LiBr solution in water.

Figure 4 indicates that the condensing pressures obtained are higher as condensing temperatures increase for each LiBr concentration. Therefore, the specific enthalpy change in the turbine is lower when condensing temperature is increased for a fixed concentration of LiBr. For that reason, the electric power generated by the steam turbine is lower as condensing temperature increases (Figure 7). This trend is the same in a Rankine cycle as in a Hygroscopic cycle. The significant advantage of the Hygroscopic cycle is the greater electric power that can be obtained with respect to a Rankine cycle (0% LiBr), as the mass concentration of lithium bromide in water increases in the cooling reflux stream (Figure 7). This is due to the lower condensing pressures reached for a given condensing temperature.

Figure 8 shows the increment obtained in the gross electric power of the HCT with reference to Rankine cycle, obtained from equation 1.

$$\Delta \dot{W}_g = \frac{\left(\dot{W}_{HCT,g} - \dot{W}_{R,g}\right)}{\dot{W}_{R,g}} \times 100 \qquad (1)$$

where:

$\Delta \dot{W}_g$ is the increment of gross electric power with reference to Rankine cycle (%).

$\dot{W}_{HCT,g}$ is the gross electric power (kWe) generated by the turbine in a Hygroscopic cycle working with the different LiBr concentrations in water.

$\dot{W}_{R,g}$ is the gross electric power (kWe) generated by the turbine in the Rankine cycle working with pure water (0% LiBr concentration).

As detailed in Figure 8, the electric power increment in the turbine with reference to Rankine cycle increases as the mass concentration of LiBr in water at the cooling reflux stream is increased. Increment in gross electric power ranges between 7.6% and 27% for the studied concentrations. For example, according to that Figure, with a concentration of 45% of LiBr solution and a condensing temperature of 30°C, electrical production respect to Rankine cycle increases above 8%. Figure 8 also shows that for the same concentration, the gross electric power increment also increases as the condensing temperature increases. Electrical production rises up to 8.5% at condensing temperature of 60°C and 45% LiBr concentration.

Electrical efficiency of a cycle is calculated by Equation 2.

$$\eta = \frac{\dot{W}_T}{\dot{Q}} \quad (2)$$

where:

η is the electrical efficiency of the steam cycle.

$\dot{W}_T$ is the electric power output of the cycle.

$\dot{Q}$ is the thermal power added to the cycle in the steam boiler.

The increment obtained in electrical efficiency of the HCT with reference to Rankine cycle is obtained from equation 3.

$$\Delta\eta = \frac{(\eta_{HCT} - \eta_R)}{\eta_R} \times 100 \quad (3)$$

where:

$\Delta\eta$ is the increment of electrical efficiency with reference to Rankine cycle (%).

η_{HCT} is the electrical efficiency (%) of the Hygroscopic cycle working with the different LiBr concentrations in water.

η_R is the electrical efficiency (%) of the Rankine cycle working with pure water (0% LiBr concentration).

Gross and net electrical efficiencies are calculated by substituting gross and net electric power of the cycle in Equation 3 respectively.

$$\dot{W}_n = \dot{W}_g - \dot{W}_c \tag{4}$$

where:

$\dot{W}_n$ is the net electrical power output of the cycle (kWe).

$\dot{W}_g$ is the gross electrical power provided by the turbine (kWe).

$\dot{W}_c$ is the electrical power consumption of pumps and dry cooler fans (kWe).

Increment in both gross and net electrical efficiency of HCT have been obtained from the data of the test plant and Equations 2 through 4.

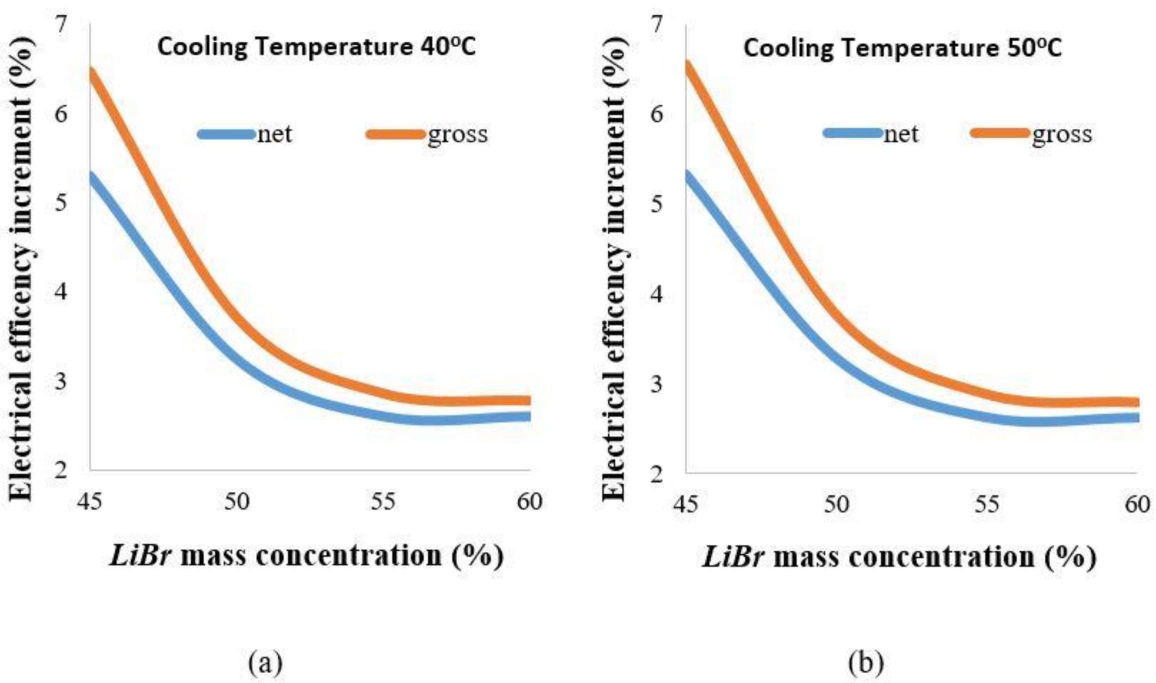

Figure 9. Increment in both gross and net electrical efficiency of HCT with respect to Rankine cycle for different mass concentrations of LiBr in the cooling reflux and: (a) cooling temperature of 40ºC, (b) cooling temperature of 50ºC.

Figure 9 shows the increment in both gross and net electrical efficiency of a Hygroscopic cycle with respect to a Rankine cycle for the different concentrations of LiBr in the cooling reflux, at cooling temperatures of 40 and 50 °C. The increment in efficiency is almost identical for those cooling temperatures being slightly higher for greater temperatures. As the mass concentration of LiBr in the cooling reflux increases, the Hygroscopic cycle provides a smaller increment in both gross and electrical efficiency compared to a Rankine cycle. For concentrations in the cooling reflux higher than 55% the increment in efficiencies is nearly constant. Therefore, the minimum efficiencies in HCT are reached for the higher concentrations with values about 2.6% and 2.8% respect to Rankine cycle for increments in net and gross electrical efficiencies respectively. It was also experimentally found that the electrical efficiency decreases when the mass concentration of LiBr in water in the cooling reflux current is decreased below 45%. Therefore, the maximum efficiency of a Hygroscopic cycle with respect to a Rankine cycle is obtained for a LiBr mass concentration in the cooling reflux of 45% (increments about 5.3% and 6.5% in net and gross electrical efficiencies respectively). For instance, a power plant of 30% net electrical efficiency is improved by incorporating HCT with the following characteristics: 45% LiBr concentration in the cooling reflux stream; cooling temperature of 40ºC; condensing temperature of 50ºC or higher. As a result, there would be an improvement of at least 8% in gross electric power output (Figure 8) and an increment about 5.3% in net electrical efficiency (Figure 9a). Therefore, net electrical efficiency of the increases by 1.59% (31.59% instead of 30%).

4. CONCLUSIONS

A novel proprietary cycle called Hygroscopic cycle which provides greater efficiency than Rankine Cycle has been experimentally studied in a test power plant. The novelty of this paper is that Hygroscopic cycle is analyzed with lithium bromide solution in water at high concentrations in order to quantify the increase in both power production and efficiency with reference to Rankine cycle. Also, the effect of high concentrations of the cooling reflux current on the condensing temperature is experimentally investigated for the first time.

Condensing temperature obtained in the Hygroscopic cycle test plant with high lithium bromide concentrations is always greater than the saturation temperature of pure water for a given condensing pressure. The minimum condensing temperature increase is 15°C respect to the steam saturation temperature (Rankine cycle) for each condensing pressure. Consequently, atmospheric temperatures and available cooling temperature that limit the condensing pressure of the steam at the turbine outlet in a traditional Rankine cycle are not limited in a Hygroscopic cycle.

The experimental results show that as the mass concentration of lithium bromide solution in water at the cooling reflux stream is increased, the condensing pressures measured at the absorber are lowered for a given condensing temperature. Condensing pressure of Rankine cycle (0% concentration) is the highest at a fixed condensing temperature compared to any lithium bromide concentration. Therefore, power output of the steam turbine and the electrical efficiency of the Rankine cycle are improved in the Hygroscopic cycle by increasing the saline concentration. Electric power generated by the steam turbine is lower as condensing temperature increases but, as the mass concentration of lithium bromide increases in the cooling reflux stream, greater electric power can be obtained with respect to a Rankine cycle. Increment in gross electric power ranges between 7.6% and 27% for the studied concentrations. Maximum efficiency of a Hygroscopic cycle with respect to a Rankine cycle is obtained for a mass concentration in the cooling reflux of 45% (5.3% and 6.5% increments in net and gross electrical efficiencies respectively). Within the range form 45 and 55%, the higher the mass concentration in the cooling reflux the smaller the increment in both gross and electrical efficiency compared to a Rankine cycle. For concentrations higher than 55% the increment in efficiencies is nearly constant (2.6% and 2.8% respect to Rankine cycle for increments in net and gross electrical efficiencies respectively).

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