Influence of cooling temperature increase in a Hygroscopic cycle on the performance of the cooling equipment

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Abstract

Power output of power plant is substantially reduced when cooling is conducted at high ambient temperatures. The problem is also intensified at locations with water scarcity. Hygroscopic cycle is a novel technology that improves Rankine cycle and solve those problems in an effective way. Hygroscopic Cycle Technology works with hygroscopic compounds that increase the cooling temperature for each output pressure of the steam turbine and uses dry coolers for refrigeration. As a result, much better cooling conditions are obtained and water consumption is avoided. Higher electrical performance is obtained without the limitation of high ambient temperatures. In this paper, Hygroscopic Cycle is experimentally studied. Results have been obtained in a test plant with a live steam generation capacity of 110 kg/h. This article shows cooling temperatures increase obtained for high mass concentrations from 45 to 65% of lithium bromide solution in water at the cooling reflux stream. The increase of the saline concentration in the cooling reflux significantly increase the cooling temperatures by more than 15°C in a Hygroscopic cycle with respect to a Rankine cycle, for the same condensing pressure. Consequently, it reduces the electrical power required by the chosen cooling system, as well as to save all the cooling water consumption needed for cooling towers in other installations.

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Hygroscopic Cycle with high concentrations is able to increase up to 17.41% the net electrical power output respect to Rankine cycle.

Keywords: Rankine cycle, Hygroscopic cycle, steam absorber, lithium bromide, dry cooler, cooling water saving, cold sink.

Nomenclature

C_i	LiBr mass concentrations (%)
EP_c	electrical power consumption of pumps and dry cooler fans (kWe)
GEP_t	gross electrical power provided by the turbine (kWe)
h_i	specific enthalpy (kJ/kg)
$\dot{m}_i$	mass flow rate (kg/s)
NEP	net electrical power (kWe)
NEP_0	net electric power output of Rankine cycle (kWe)
$NEP_{\%}$	net electric power output of HCT for different LiBr concentrations (kWe)
q_d	heat of dilution (kJ/kg)
$\dot{Q}_d$	heat transfer rate due to heat of dilution (kW)
$\dot{Q}_r$	heat transfer rate dissipated by the dry coolers (kW)
Tc	condensing temperature (ºC)
T_i	temperature (ºC)
Tv	steam saturation temperature (ºC)
$\Delta(NEP)$	net electrical power increase (%)

Acronyms

ACC	air-cooled condenser
CSP	concentrating solar power
HCT	Hygroscopic Cycle Technology
ORC	Organic Rankine Cycle
PLC	programmable logic controller
SCADA	Supervisory Control and Data Acquisition
U.S.	United States

Chemical symbols

$CaCl_2$	calcium chloride
LiBr	lithium bromide
LiCl	lithium chloride
NaCl	sodium chloride
$NaNO_3$	sodium nitrate
NaOH	sodium hydroxide

1. INTRODUCTION

Climate change poses immediate risks on the supply of fresh water for power generation as water scarcity becomes more frequent and more severe [1]. The growing global energy demand accentuates the decrease in the availability of water resources and leads to a worsening of water quality due to the increase in pollutant emissions [2]. It has been estimated that there would be a 40% increase in energy and a 30% increase in water demand by 2040 [3]. Over 40% of the global population live in river basins with severe water shortages, mainly in northern and southern Africa and in Central and South Asia [4]. Seawater desalination is being used to alleviate this problem, but the process is intensive in terms of energy demand and large amount of unwanted brine by-product is obtained. Therefore, efforts to optimize and reduce water consumption by power generation facilities is of utmost importance in the face of society and the environment [5]. As United Nations has concluded, addressing water scarcity is one of the greatest challenges of the century [6]. Power plants require water for electricity generation and consequently, decreased water availability limits power generation. Water withdrawal for electricity generation in the United States (U.S.) accounts for approximately half the total freshwater withdrawal [7]. The effect of changes in water availability on the U.S. electricity mix using econometric approaches was studied in [8]. According to their results, long-run water scarcity or abundance will affect utility decisions about the construction of new power plants, affecting both the exposure of the electricity mix to water scarcity and the marginal source of electricity generation that will offset displaced generation. Water consumption in thermoelectric plants in China increased from 1.6 billion m^3 to 3.8 billion m^3 from 2002 to 2010 [9]. In countries such as China, spatial layout could further aggravate national water scarcity. Fang et al. [10] built an optimization model to adjust the spatial layout of power generation by redistributing China's provincial electricity generation tasks based on provincial water scarcity and energy resources. Gu et al. [11] suggested that a cooperative relationship between water and energy conservation efforts should be an important factor in creating policies that encourage simultaneous savings of both resources in China. In Europe, thermoelectric power plants generate 74% of total electricity supply [12]. European energy sector therefore strongly depends on the availability of water resources and on the temperatures of water for cooling.

Thermoelectric power plants that use turbines to generate electricity need to cool the steam passes through the turbine before it can be reused in the steam cycle. Rankine cycle is the basic thermodynamic cycle which is a large consumer of water for the feeding the cycle itself, for cleaning and for the cooling system [13]. Water consumption also depends on the type of technology used, cooling system selected, climate and weather conditions around the power plant and cycle performance. One way to increase the performance of the Rankine cycle is to reduce the temperature of the cold sink. This requires a suitable cooling system that allows condensing the turbine exhaust steam to the lowest possible thermal level. There are multiple types of cooling technologies to condense steam, including once-through (or open circuit), evaporative cooling (cooling towers), and air condensers. The amount of water used by each power plant is highly dependent on its cooling technology [3]. Figure 1 reflects the cooling water consumption [14] in a high efficiency thermoelectric plant, using cooling towers, based on the power output of the plant.

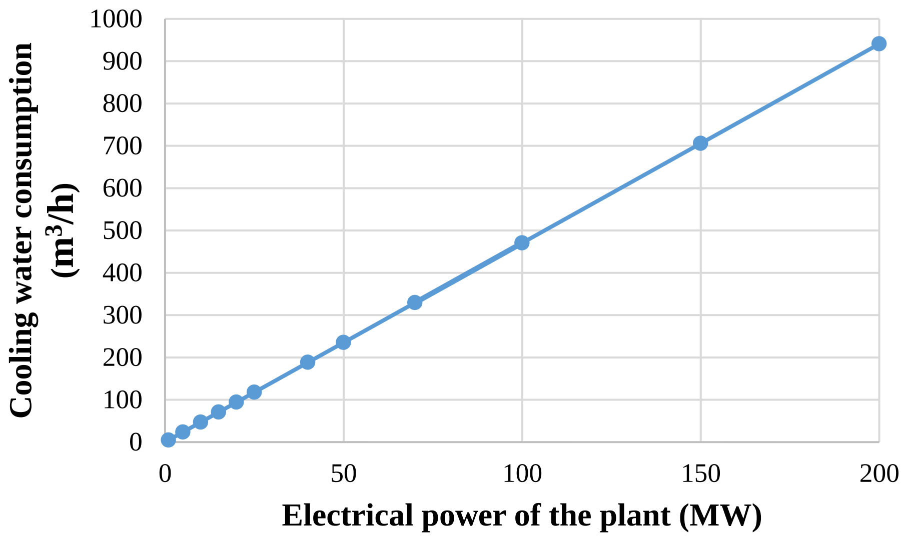

Figure 1. Cooling water consumption for different electrical power outputs of power plants.

In the literature, many investigations to reduce water consumption in thermoelectric power cycles have been presented by using different cooling systems. Thermodynamic analysis of the integration of absorption refrigeration systems into Rankine power cycles to reduce water consumption has been done in [15]. The simulation for a 50 MW power plant estimated that the water savings range from 1.33 to 6.70 m^3/h per unit steam through the cycle. Also, the water savings range from 1.12 to 5.58 m^3/MWh. In [16], a mathematical model to study the performance enhancement of combined cycle power plant using inlet air cooling by exhaust heat operated ammonia-water absorption refrigeration system was presented. Energy and exergy analyses performed in that work reveal that with the use of this type of chiller, for the same fuel consumption, the net power output of the plant increases by 2.8%, the thermal efficiency by 1.193% and the exergy efficiency by 1.133% thereby improving the overall performance appreciably. According to the author, this method will work very efficiently in Indian atmospheric conditions which are hot in most part of the year, but the required investment was not presented in the article. A theoretical analysis on increasing thermal efficiency of Rankine cycles by using refrigeration cycles was done by [17]. Organic Rankine cycle (ORC), Goswami cycle and Kalina cycle are the major cycles that have been developed for the conversion of low grade of heat into electricity. Most of the recent investigations about Rankine cycle focus on ORC [18]. ORC uses working fluids with low boiling points, instead of steam, to recover heat from a lower temperature heat source. [19] studied the effect of flow losses in condenser on the performance of ORC. The maximum relative increase of total irreversibility is 9.7%, while the maximum relative decrease of net work output, thermal efficiency and exergy efficiency are 16.1%, 17.0% and 16.9%, respectively. Obviously, the influence of the design and operation of the refrigeration device has an important effect on the cycle performance. In [20], Kalina cycle uses absorption condensers for heat discharge, thus makes great temperature difference of work solution in the endothermic process and small temperature difference of basic solution in the exothermic process at the same time. Energy analysis for a Rankine-Kalina combined cycle was performed by Murugan & Subbarao [21]. This cycle produces higher power output and is more efficient than a Rankine steam cycle. Goswami cycle uses binary mixture to produce power and refrigeration simultaneously in one loop [22]. A mixture of ammonia and water is pumped from the absorber to high pressure. It is then split into two streams which mixes and enter the desorber after recovering heat. 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. [23] presents the optimization of the operation of a concentrated solar power plant with dry cooling over a year, evaluating the molten salts storage, the power block and the air-cooling system as a function of the climate and atmospheric conditions. The annual production cost of electricity is 0.16 €/kWh and the investment required is 265 M€, both slightly higher than when wet cooling is used, but with negligible water consumption. In [24], different feasible integrated configurations were proposed and thermodynamically evaluated for cogeneration of power and fresh water/cooling, and trigeneration of power, cooling and fresh water. The results showed the configurations that utilize steam extraction with a lower temperature and pressure were more efficient. The ideal locations for thermoelectric solar plants, with a high degree of annual sunshine, are encountering barriers due to the limitation of water in the area. These circumstances restrict the electrical production since they demand a greater pressure of condensation [25]. These factors can penalize the performance and, consequently, the success of the plant. Even when the availability of water is affordable, the use of cooling towers brings with it an increase in operating costs, water treatment and environmental risks (legionella) that make it difficult or even impossible to install those cycles using wet cooling. Air condensers (condensation of water vapor through indirect contact with ambient air) solve the problem partially. Its price, the required space and its electricity consumption make its installation neither profitable nor attractive in most of the cases. In the problems discussed above is where there really is room for improvement.

Recently, a new technology that significantly reduces water consumption for cooling was developed by Rubio Serrano [26] and co-workers. That technology is called Hygroscopic Cycle Technology (HCT). One of the main problems of Rankine cycles arises when cooling is conducted at high ambient temperatures. In that cases, power output of the power plant is considerably reduced or may even be forced to stop the electrical generation. The problem is also intensified by water scarcity [27] for cooling. HCT overcomes the previously cited cooling problems in power plants using steam cycles in a practical and efficient way. It is a power cycle similar to the Rankine cycle and characterized by working with hygroscopic compounds. That compounds optimize the steam condensation of the turbine output. For this purpose, the condensing temperature is increased [28] for a given condensing pressure. HCT can replace or be added to a Rankine cycle for any electric power generation plant [29] such as combined cycles, thermoelectric power plants, biomass power plants, thermosolar power plants and nuclear power plants. The new technology is very different to Goswami and Kalina cycles. The main differences are that HCT is not limited to conversion of low grade of heat into electricity, and the binary mixture does not use neither an external heat source nor a desorber to separate the steam from the other fluid. There is only an absorber in which the steam is directly condensed by absorption due to the different concentration of hygroscopic compounds between the stream inlets [30]. Only a few investigations have been published about HCT, because it was recently developed. The Hygroscopic Cycle has been in the state of the art since 2010 as "Rankine Cycle with absorption stage using hygroscopic compounds" [31]. In 2015 the installation of a test plant of the Hygroscopic cycle was completed. It was the first pilot plant worldwide that reproduces HCT. This plant is located in Gijón (Spain) and is owned by IMASA, INGENIERÍA Y PROYECTOS S.A [32]. The most important elements of HCT are the absorber and the associated cooling system. In the absorber, the condensation of the steam coming from the turbine takes place because of the absorption phenomena. It is due to the concentration of hygroscopic compounds in the cooling reflux stream provided by the cooling system. As a result, the cooling temperature in the absorber is higher than to the one of the Rankine cycle for a given condensing pressure. Regarding the cooling system, the equipment used in this technology to dissipate the heat of condensation are air coolers, also called dry coolers. Those devices are heat exchangers in which the hot fluid passes through a tube bundle [33] and is cooled by an air stream driven by fans of high electrical efficiency, whose speed is regulated based on the ambient temperature [34]. The advantages of dry coolers over cooling towers are that consumption of cooling water is cancelled, as well as the tower purges [35], plumes are removed [36], lower environmental and acoustic impact, less annual electricity consumption and lower operating and maintenance costs [37]. The advantages of dry coolers with respect to air cooled condensers [38] are that the former are cheaper, lower anual electricity consumption, smaller size and thus less civil works [39]. The main disadvantage of dry coolers is that they cannot achieve the same cooling temperatures (close to ambient) as in cooling towers (dry bulb temperature). This problem is solved by HCT because the cooling temperature is increased by using hygroscopic compounds in the cooling reflux. The benefits of incorporating the innovative HCT to an existing power plant have been published in [30]. It is the first world industrial scale reference that uses HCT. It is a 12.5-MW biomass power plant located in Spain, in which the boiler blow-downs are used as hygroscopic compounds to condense the turbine outlet steam in the absorber. The condensing temperature is increased above the saturation temperature of the pure steam for a given pressure. The new technology allows the plant to refrigerate the steam even with high ambient temperatures, increase the net electrical efficiency of the plant, as well as saving the cooling tower and therefore, avoiding cooling water consumption [30]. The actual amount of raw water saved in that plant with HCT is 229,200 m^3 per year.

In the literature there are not any studies about the relationship between the different parameters governing the HCT. As it was previously explained, cooling temperature is one of the main parameters of HCT, directly related to the cooling system. The dry cooler has high electric efficiency fans whose speed is regulated based on the ambient temperature. Therefore, depending on the cooling temperature reached, HCT will be able to work under different ambient conditions. Cooling temperature depends on the concentration of the cooling reflux. Consequently, it is very relevant to determine the relationship between cooling temperature and hygroscopic compounds concentration in the cooling reflux stream.

The main objective of this paper is to experimentally quantify the benefits of the cooling system used in the HCT, with respect to the classic Rankine refrigeration system. The novelty of the present work is that instead of using only the steam boiler blow-downs, HCT is also studied with a different hygroscopic compound and at higher concentrations in order to increase the effect of raising the cooling temperature. The selected compound was lithium bromide (LiBr), mainly used in absorption refrigeration [40] for cold production, since it is a highly hygroscopic and soluble salt in all working steps of the steam cycle. LiBr shows an increase of solubility in water as the temperature of the solution is increased [41]. Also, the effect of increasing LiBr concentration on the energy consumption of the dry coolers and net electrical power output is experimentally studied in this paper.

2. MATERIALS AND METHODS

2.1 Experimental setup

The experimental values used in this article were obtained in an HCT test plant located at Gijon – Spain (43°32′N 5°42′W). It is the first worldwide test plant reproducing the HCT. The plant includes the main equipment and materials necessary to analyze HCT. Those equipment and materials are also available and scalable at industrial level. Figure 2 shows a view of the HCT test plant.

Figure 2. HCT test plant with detail of the dry coolers used.

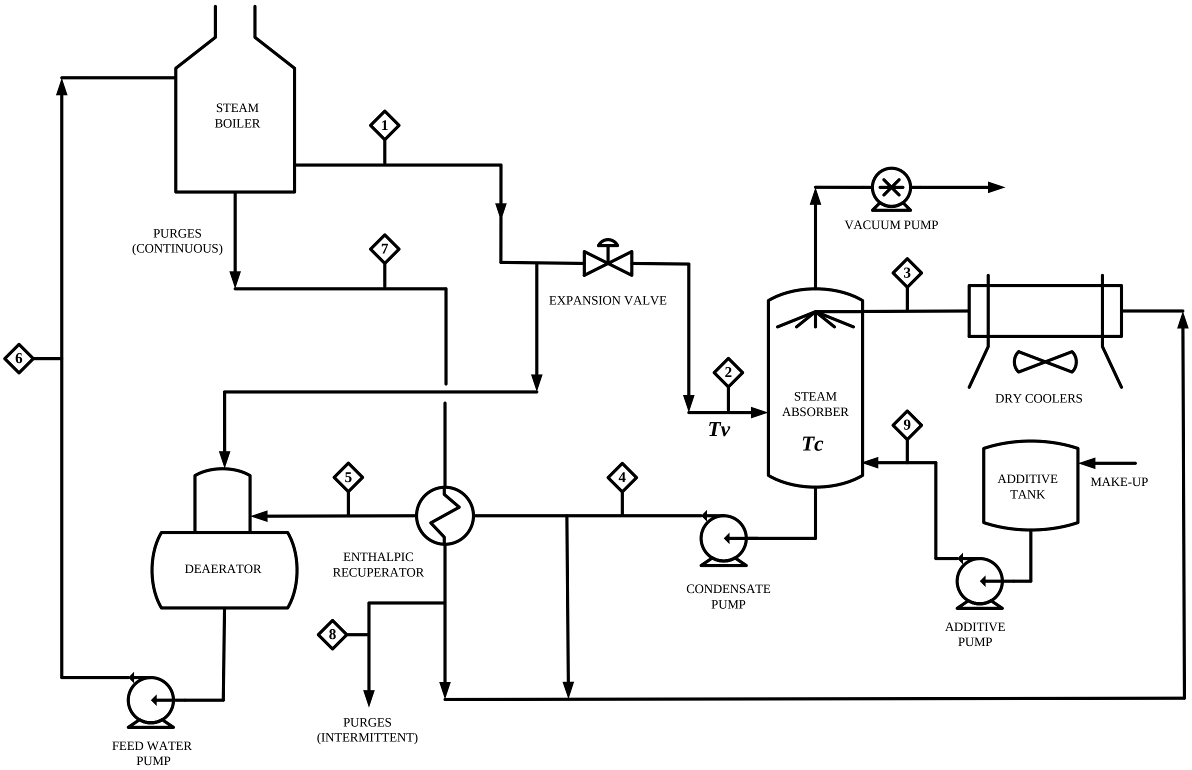

Figure 3. Process diagram of the HCT test plant.

Figure 3 presents the process diagram of the HCT test plant. The superheated steam (1) is produced in a 100-kW natural gas boiler. It is a pyro-tubular boiler with steam generation capacity of 110 kg/h at 13 barg and maximum temperature of 200°C. The outlet of the boiler is equipped with a high efficiency droplet separator to minimize the dragging of salts into the turbine. Instead of a turbine, the test plant uses an expansion valve. It makes the plant cheaper and easier to manage. With this arrangement it is possible to calculate the power output that would have produced a steam turbine under test conditions. The isenthalpic expansion produced in the valve is registered in a programmable logic controller (PLC) [42]. It is programmed to calculate the instantaneous electrical power provided by a turbine based on the experimental data measured at the outlet of the valve. Also, a Supervisory Control and Data Acquisition (SCADA) system [43] gathers, controls and supervises all data. The scale of the plant produce a power output of 30 kWe. The valve exhaust steam (2) is heading for the steam absorber where it is mixed with the condensed liquid stream called cooling reflux (3). This stream is rich in hygroscopic compounds and has a higher salt concentration than the steam. The steam absorber is the most characteristic component of HCT. The condensation of the steam coming from the turbine takes place in the steam absorber because of the absorption phenomena. It is due to the concentration of hygroscopic compounds in the cooling reflux stream provided by the cooling system. Due to absorption process, the condensing temperature of the vapor in the steam absorber is greater than the saturation temperature of exhaust steam ($Tc > Tv$ in Figure 3), for the same condensing pressure [44]. Vacuum pump extracts air and other non-condensing gases from the steam absorber. According to Figure 3, the condensed fluid (4) at the outlet of the steam absorber is divided into two streams. One stream (5) is directed towards the deaerator unit, where non-condensable gases are removed. The other stream is recirculated as cooling reflux (3), flowing through a set of dry coolers where the heat of condensation is removed. An air current at ambient conditions is driven by high efficiency electric fans. The air stream cools a copper tube-bundle, through which cooling reflux stream passes. Dry coolers guarantee the cooling temperature of the system. The condensed fluid (6) exiting the deaerator is pumped to the boiler. Thermal energy of the boiler blow-down (7) is recovered in a closed heat exchanger. That equipment is called enthalpic recuperator and provides energy to the stream that feeds the deaerator (5). Thermal and chemical recovery of these purges is essential for the right operation and electrical performance of HCT. In order to maintain chemical equilibrium in the cycle, a fraction of the boiler blow-down (8) is intermittently removed from the system. In the additive tank (2-m^3 atmospheric tank) the make-up is done. Through this tank both chemical additives and LiBr dissolved in water are introduced into the cycle (Figure 3). It allows control of LiBr concentration of in the cooling reflux stream. Additives are a mixture of amines [45] used to avoid formation of scales and protect metallurgy against corrosion due to dissolved gases.

2.2 Instrumentation and uncertainties

In the test plant, power meters (accuracy ±0.1%) were installed at the dry coolers and pumps to measure power consumption. Numerous cooper-constantan thermocouples (T-type, with uncertainty ±0.2ºC) were used to measure temperatures at the inlets and outlets of the main equipment described above. Platinum resistances (Pt100, accuracy ±0.1ºC) were located at inlets and outlet of the absorber to obtain more accurate temperatures. Pressure sensors (Aplisens PCE-28, accuracy ±0.5%) were used to measure pressures at inlets and outlets of the devices. Flowmeters (accuracy ±0.5%) were mounted in each stream to measure the all the mass flow rates. Accuracy of the data acquisition equipment used is 0.004%. There are purges in all streams for taking samples of fluid. The samples were used for measuring LiBr concentrations (estimated uncertainty about ±0.25%). Calculated electrical powers have an estimated uncertainty of ±0.15%, based on the accuracy of the direct measuring instruments and data acquisition equipment.

2.3 Mathematical model

Figure 4 shows the steam absorber and the cooling system with the connections with the rest of the HCT components.

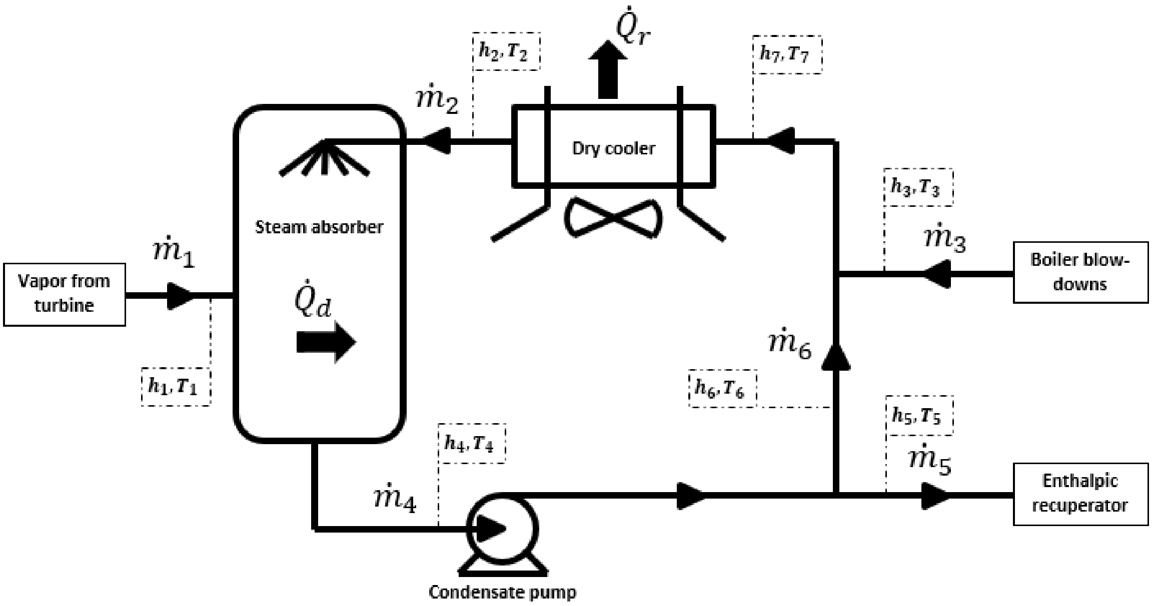

Figure 4. Scheme of steam absorber and cooling system in HCT.

In Figure 4, the following notation is used:

$\dot{m}_i$: mass flow rates (kg/s) of the different streams. Specifically, $\dot{m}_1$ is the steam mass flow rate from the turbine and $\dot{m}_2$ is the mass flow rate of the cooling reflux stream.

h_i: specific enthalpy values (kJ/kg) at the different points. They depend on temperature, pressure and LiBr concentration. h_1 is the enthalpy of the turbine steam exhaustion.

T_i: temperature values (ºC) at the different points. T_2 is the cooling temperature of the cooling reflux stream.

$\dot{Q}_r$: heat transfer rate dissipated by the dry cooler (kW).

$\dot{Q}_d$: heat transfer rate due to heat of dilution (kW).

q_d: heat of dilution (kJ/kg) [46] that is defined as the heat exchanged with the medium when an additional amount of solvent is added to a solution. This heat depends on the initial concentration and the amount of solvent added.

For the mathematical development, the following assumptions and simplifications are considered:

- All the elements (steam absorber, pipes, pumps, etc.) are adiabatic, except for the dry cooler.
- Kinetic and potential energy changes are negligible.
- Condensate pump power input is the necessary to overcome the pressure losses in that part of the circuit. That power consumption is very small compared to the other power terms and it will be neglected.

Equations (1), (2) and (3) express the mass balances at steady flow conditions of the streams in Figure 4.

$$\dot{m}_1 + \dot{m}_2 = \dot{m}_4 \tag{1}$$

$$\dot{m}_4 = \dot{m}_5 + \dot{m}_6 \tag{2}$$

$$\dot{m}_6 + \dot{m}_3 = \dot{m}_2 \tag{3}$$

Energy balance of the steam absorber at steady flow is given by Equation 4.

$$\dot{m}_1 h_1 + \dot{m}_2 h_2 + \dot{Q}_d = \dot{m}_4 h_4 \tag{4}$$

Equation (5) states the energy balance for the single-stream (one-inlet and one-outlet) steady-flow system corresponding to the cooling reflux in the dry cooler.

$$\dot{Q}_r = \dot{m}_2 (h_7 - h_2) \tag{5}$$

Energy balance of the system excluding the steam absorber is given by Equation (6).

$$\dot{m}_3 h_3 + \dot{m}_4 h_4 - \dot{Q}_r = \dot{m}_5 h_5 + \dot{m}_2 h_2 \tag{6}$$

Heat transfer rate due to heat of dilution is calculated by Equation (7).

$$\dot{Q}_d = \dot{m}_2 q_d \tag{7}$$

According to the assumptions above mentioned, it can be considered that:

$$h_4 \approx h_5 \approx h_6 \text{ and } T_4 \approx T_5 \approx T_6 \tag{8}$$

LiBr mass balance for the steam absorber is given by Equation (9).

$$\dot{m}_1 C_1 + \dot{m}_2 C_2 = \dot{m}_4 C_4 \tag{9}$$

Where C_i are the LiBr mass concentrations at the inlets and outlets of the absorber. Note that $C_1 = 0$ because it is pure steam.

The set of equations (1) through (9) provides a theoretical relationship between LiBr concentration of the cooling reflux (C_2) and cooling temperature (T_2) at different condensing pressures in the absorber.

2.4 Limitations and experimental validation

Results obtained in the test plant have been contrasted by theoretical models for low concentrations of hygroscopic compounds. It is widely known that when the mass concentration is less than 1%, the relationship between ebulloscopic increase and concentration is linear [47]. This is also coherent with variation of heat of dilution with low concentrations of LiBr (linear trend and low slope) [46]. At industrial scale, results have been validated in [30] for low concentrations. On the contrary, for actual solutions with high concentrations, the increase in boiling point and the decrease in vapor pressure do not follow a linear but a polynomial trend when the concentration of hygroscopic compounds increases. The values obtained in the test plant for the solution of LiBr in water with high concentrations were corroborated with the diagrams of Dühring [48]. Mass and energy balances performed in the test plant were verified with the equations in section 2.3 and the tables of properties for LiBr solution in water [49]. Consequently, experimental mass and energy balances are effective for other process conditions and provide a tool for designing any power plant that works with a steam and high concentrations of LiBr.

Nonetheless, in order to obtain optimized actual values at high concentrations of hygroscopic compounds, some experimental restrictions have to be considered. In the specific case of LiBr, it is experimentally verified that the difference in optimum mass concentrations between the boiler feed stream and the boiler blow-downs current is 5%. With differences in concentration greater than 5%, the thermal energy consumption in the boiler would increase, as well as the thermal energy dissipated in the dry cooler, due to the great increase in heat of dilution. With differences lower than 5%, the mass flow rate of boiler blow-downs is to be increased and, consequently, the electrical self-consumption of the cycle would be significantly increased. Besides, for an optimized design, the temperature difference of the cooling reflux stream between the inlet and outlet of the dry cooler ranges from 7 to 14°C.

Maximum temperatures and gauge pressures in the test plant are limited to 200ºC and 13 barg respectively because of the boiler installed. The steam turbine is simulated with a software that uses the previously mentioned SCADA system, certified by Navantia [50]. For the simulation, superheated steam at 60 bar(a) and 500ºC is introduced at turbine inlet. Maximum ambient temperature at the location of the plant is 35 ºC. Mass concentration of LiBr in water ranges from 45 to 65%. Concentrations lower than 45% correspond to very low values of heat of dilution [46] and consequently, results barely improve respect to the ones obtained with the boiler blow-downs of the Rankine cycle. On the other hand, 65% is the maximum solubility of LiBr in water (saturated solution) for the working temperature range of the test plant [41].

3. RESULTS AND DISCUSSION

According to the experimental results obtained in the test plant, the concentration of hygroscopic compounds in the cooling reflux stream has a very significant the influence on the cooling temperatures required by the HCT (Figures 5 and 6).

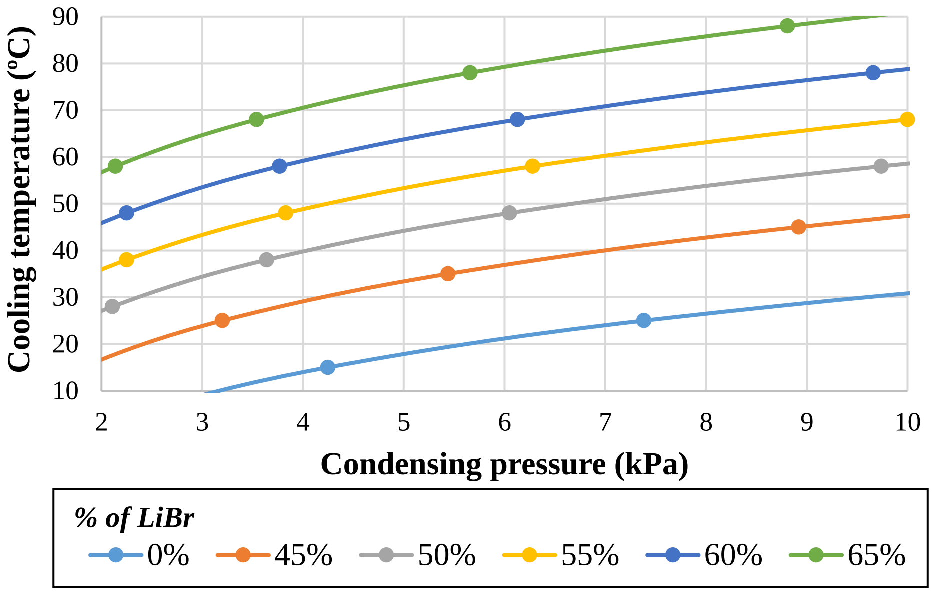

Figure 5. Cooling temperatures required for condensing pressures between 2 and 10 kPa(a) for different mass concentrations (%) of LiBr solution in water.

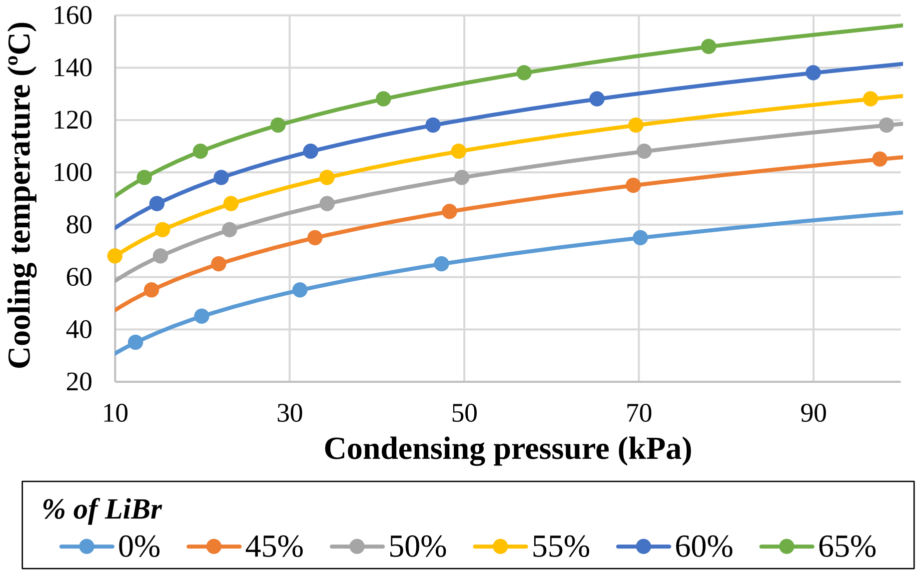

Figure 6. Cooling temperatures required for condensing pressures between 10 and 90 kPa(a) for different mass concentrations (%) of LiBr solution in water.

As reflected in Figures 5 and 6, by increasing the mass concentration of the LiBr solution at the cooling reflux stream (stream 3 of Figure 3), the cooling temperatures required in an HCT for condensation are higher for a given pressure. These temperatures and pressures have been measured at the steam absorber. Therefore, given the nonvolatile nature of LiBr salt at those temperatures, the higher the concentration, the higher the cooling temperature increase with reference to Rankine cycle (0% LiBr in Figures 5 and 6) for each condensing pressure.

According to Figure 3, the outlet steam from the expansion valve (stream 2) is mixed with the cooling reflux (stream 3) in the steam absorber. Due to absorption, condensation takes place at a greater temperature than the saturation temperature found in the steam tables, for each pressure. This is a great advantage and novelty of using the present technology in a steam cycle. The cold reservoir temperature limits the condensing temperature and pressure of the turbine outlet steam in a traditional Rankine cycle. On the contrary, due to the significant increase in the actual condensing temperature in the steam absorber, there is not that limitation for the cold reservoir (ambient temperature) with HCT. Because of the condensation conditions of HCT, the required cooling temperatures are increased. Figure 5 shows that, for a condensing pressure of 8 kPa(a), the Rankine cycle (0% concentration of LiBr in water) requires a cooling temperature of 26.5°C vs. 62.5°C in HCT with a mass concentration of 55% of LiBr solution in water. In that case, the technology increases the cooling temperature by 36°C and high ambient temperatures are tolerable. Figures 5 and 6 also indicate that for the same cooling temperature, the condensing pressure is much lower when increasing the LiBr concentration and therefore, the turbine power output can be increased. These advantages are very significant in the viability of a steam cycle since the HCT allows working with the minimum pressures tolerable by current condensing steam turbines. Also, HCT is not limited neither by the ambient conditions (or cold sink temperature) nor the cooling system used. In this HCT, a battery of dry coolers is used, totally avoiding water consumption for cooling.

Experimental results presented in Figures 7 through 9 show the differences between Rankine cycle and HCT as regards required power consumption as well as cooling water consumption demanded by the cooling towers.

Figure 7 shows that for a condensing pressure of 7 kPa(a), the necessary cooling temperature in a Rankine cycle is 24°C. For that pressure, cooling temperature is 62°C (38 °C higher than Rankine) with HCT and 55% LiBr. For the specified conditions, Rankine cycle would require a cooling tower, with a significant consumption of cooling water. HCT can reach the temperatures detailed in Figure 7 with a dry cooler of high electrical efficiency; even for an ambient temperature over 50 °C. Consequently, HCT is not limited by the cold sink [51] temperature as in Rankine cycle. It provides greater availability to the power plant.

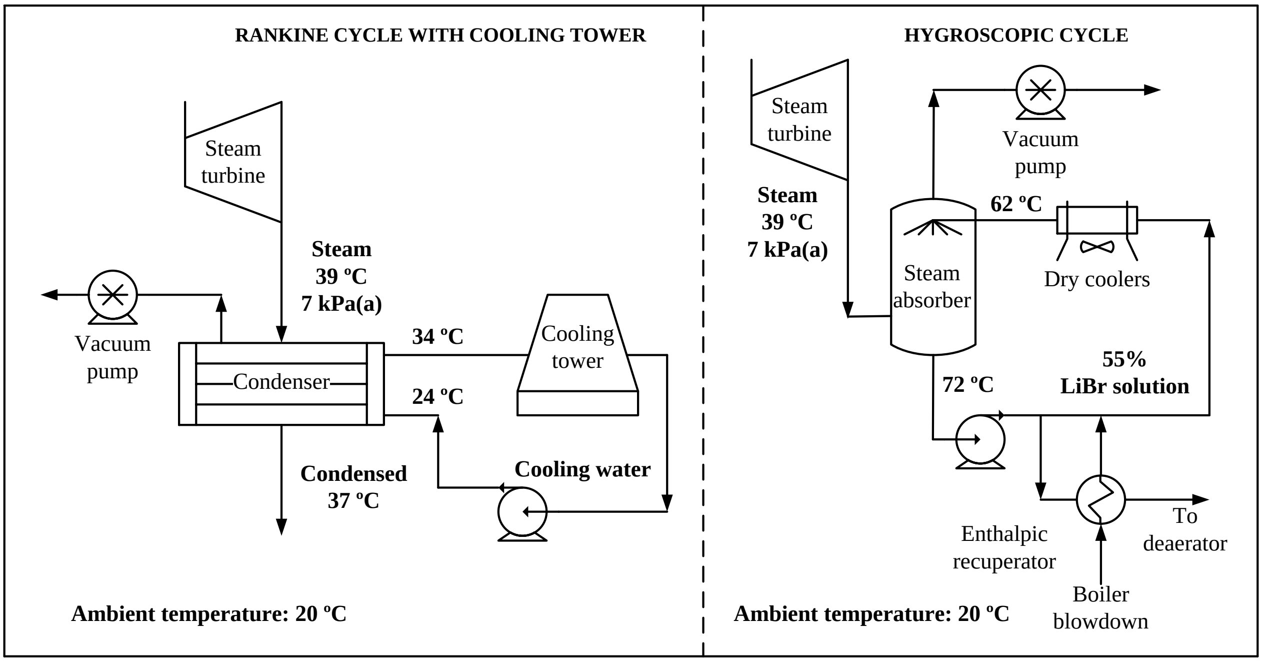

Figure 7. Cooling temperature increase on a Hygroscopic cycle with respect to a Rankine cycle with cooling towers for Rankine cycle at the same condensing pressure.

Experimental results presented in Figures 7 and 8 indicate that for an ambient temperature of 20°C, condensing pressures of 7 kPa(a) can be achieved with HCT. Those values cannot be reached by means by means of a traditional air-cooled condenser (ACC), or at least not in an economical way [52]. Electricity consumption of the fans in HCT are much lower than those required by cooling tower fans of Figure 7, and further less than those of an ACC detailed in

Figure 8. That power consumption depends on the required cooling temperature and the ambient temperature.

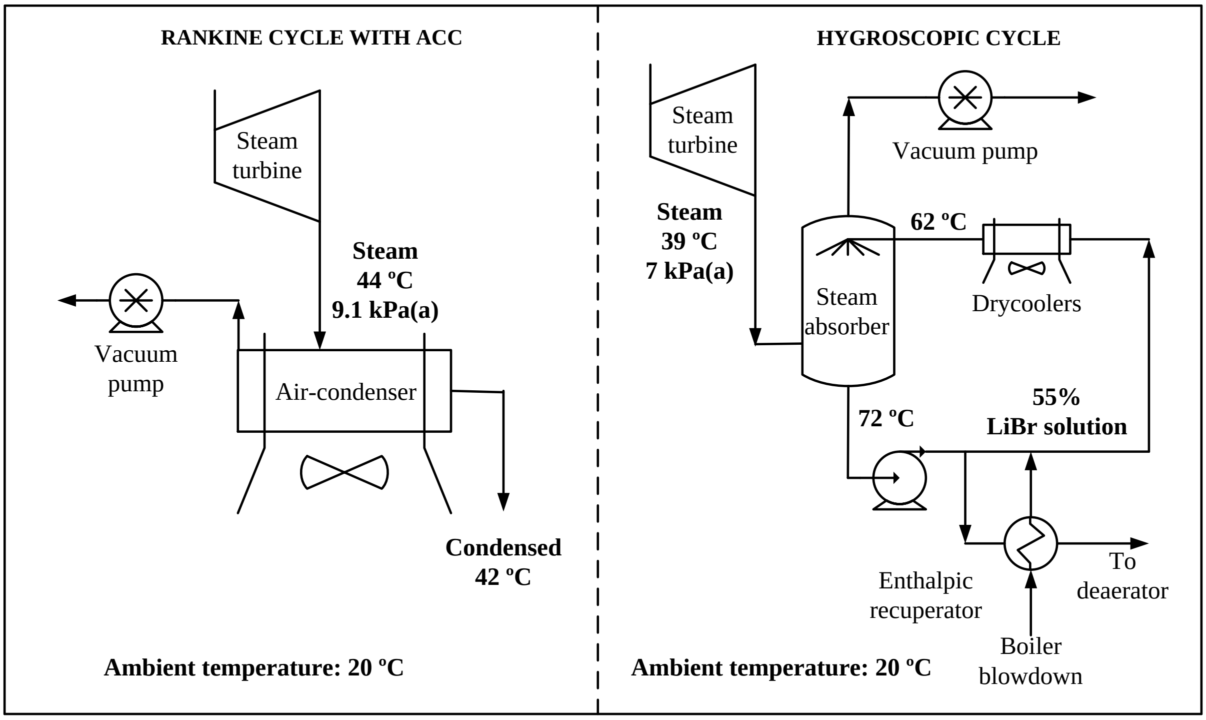

Figure 8. Cooling temperature increase in Hygroscopic Cycle with respect to a Rankine cycle with air cooled condenser (ACC) at the same ambient temperature.

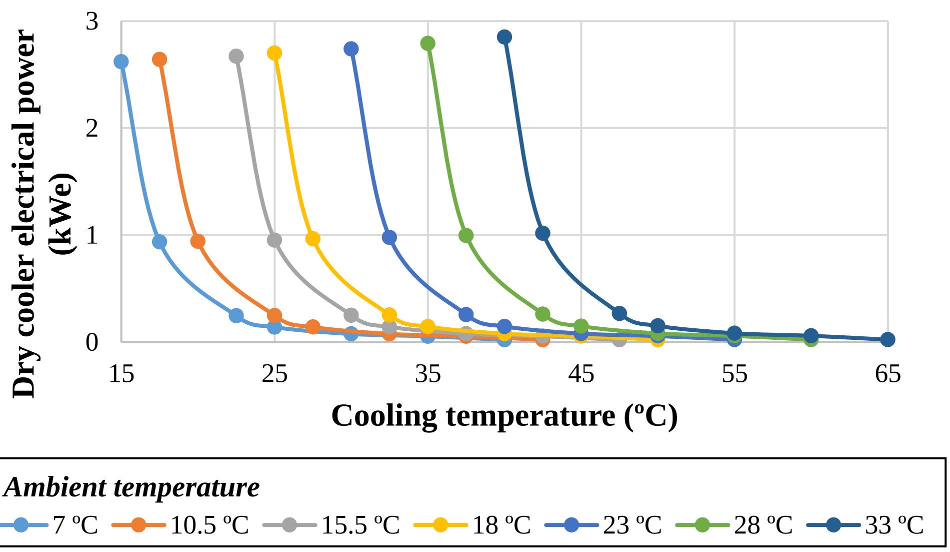

Figure 9. Electrical consumption of dry coolers for the cooling temperatures required at different ambient temperatures.

Figure 9 shows the power consumption of the dry coolers of the test plant detailed in section 2, for the cooling temperature required (stream 3 at Figure 3). For a given ambient temperature, electricity consumption of the dry cooler fans decreases exponentially when increasing cooling temperature. Therefore, the increase in the cooling temperature required by the dry coolers of HCT reduces the electrical power demand of the cooling equipment, as opposed to the Rankine cycle, whose cooling temperature for the same condensing pressure is always lower. The overall consequence is an increase in the net electrical power output of the power plant, by reducing self-consumption.

Power output provided by the turbine can be increased by lowering the condensing pressure at the same cooling temperature. According to Figure 5, for a cooling temperature of 30ºC, condensing pressure is 9.7 kPa(a) in Rankine cycle (0% LiBr) and 4.3 kPa(a) in HCT (45% LiBr). Steam turbine is simulated under the following conditions: steam inlet at 6 MPa(a) and 500ºC; mass flow rate 100 kg/h; isentropic efficiency 82% and electrical efficiency 97%. The electrical power output of the simulated turbine is 27.55 kWe for the Rankine cycle and 29.65 kWe for HCT (45% LiBr). Therefore, for cooling temperature of 30ºC, HCT provides a gross output electrical power 7.6% greater than Rankine. From figures 5 and 6, it can be generalized that gross electrical power (GEP) provided by HCT is greater than GEP provided by Rankine cycle for the same cooling temperature. Also, the greater the concentration of LiBr, the greater the GEP output.

Net electrical powers are given by Equation (10).

$$NEP = GEP_t - EP_c \tag{10}$$

where:

NEP is the net electrical power (kWe)

GEP_t is the gross electrical power provided by the turbine (kWe)

EP_c is the electrical power consumption of pumps and dry cooler fans (kWe).

Increase in net electrical power output of HCT respect to Rankine cycle (%) at the same cooling temperature can be obtained by Equation 11.

$$\Delta(NEP) = \frac{NEP_{\%} - NEP_0}{NEP_0} \times 100 \quad (11)$$

where:

$\Delta(NEP)$ is the net electrical power increase (%).

$NEP_{\%}$ is the net electric power (kWe) output of HCT for different mass concentrations of LiBr in water

NEP_0 is the net electric power (kWe) output of Rankine cycle

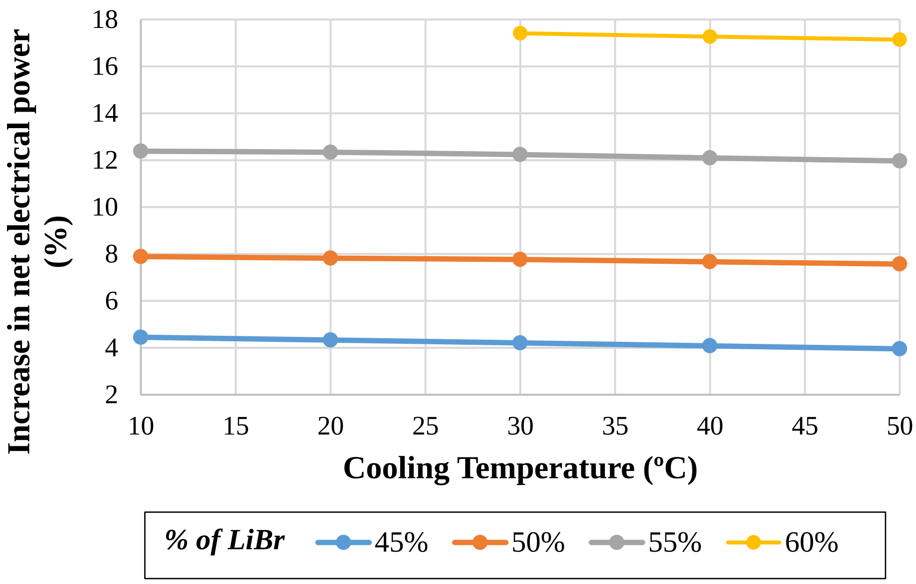

Figure 10. Increase in net electrical power output of HCT respect to Rankine cycle vs. cooling temperature at different LiBr concentrations.

Figure 10 presents the results obtained for the increase in NEP output of HCT respect to Rankine cycle for each cooling temperature, at different LiBr concentrations. It shows that Δ(NEP) is greater as the mass concentration of LiBr in water in the cooling reflux stream increases. Nonetheless, for each LiBr mass concentration, Δ(NEP) is lower as the cooling temperatures increase. For instance, with 60% mass concentrations of LiBr in the cooling reflux stream, at cooling temperatures of 30 ºC and 40 ºC, Δ(NEP) is 17.41% and 17.27% respectively.

4. CONCLUSIONS

One of the main difficulties of thermoelectrical power generation arises when cooling is conducted in locations with high ambient temperatures and water scarcity. HCT is a new technology that overcomes those cooling problems in a practical and efficient way. Cooling temperature is increased by using hygroscopic compounds in the cooling reflux. HCT has been experimentally studied in a test plant with the hygroscopic salt LiBr at high mass concentrations ranging from 45 to 65%.

Experimental results show that a high concentration of LiBr in the cooling reflux stream of a Hygroscopic cycle increases by over 15 ºC the cooling temperature required for a given condensing pressure, with respect to a Rankine cycle. For instance, cooling temperature increases by 36°C in HCT with a mass concentration of 55% of LiBr solution in water. Experimental results demonstrate that as cooling temperature is increased, electricity consumption of the dry cooler fans decreases exponentially, for a given ambient temperature.

HCT translates into better cooling conditions since power consumption of the cooling system is significantly reduced and it saves the entire consumption of cooling water, without limited ambient temperature (cold sink) to reach the minimum condensing pressure tolerable by commercial condensing steam turbines. It also increases the availability of the power plant, even under extreme ambient conditions.

HCT with high concentrations of LiBr considerably contributes to improve the net electrical power output of the steam cycles (up to an increase of 17.41% respect to Rankine net electrical power). It solves the great problem of high electrical efficiency power plants that require cooling water in order to reach the lowest possible temperatures and pressures at condensation.

Hygroscopic cycle is applicable to new power plants and can be incorporated to existing plants that use Rankine or combined cycles. Potential applications of HCT are also any industrial processes that condense vapor with the aim of improve condensing and cooling conditions and take advantage of the associated benefits. It implies the use of salt mixtures and the increase in cooling temperature will depend on the concentration of these solutions. The choice of these compounds must ensure that in addition to being less volatile than water, they have to be soluble in all the steam cycle operation points in order to avoid the formation of precipitates that would increase scale and corrosion in the equipment. Therefore, great potential is opened here for the future investigations of HCT with different hygroscopic compounds such as sodium chloride ($NaCl$), calcium chloride ($CaCl_2$), sodium hydroxide ($NaOH$) or lithium chloride ($LiCl$). Some salts show an endothermic effect when they are diluted, such as sodium nitrate ($NaNO_3$). This means the condensation heat decreases in the absorber. This effect can be of particular interest for concentrating solar power (CSP) plants, because the performance of the turbine could be kept high even on very hot days.

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