

Influence of LiBr concentration in the generation of superheated vapor for a Hygroscopic Cycle

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Abstract

The novel proprietary Hygroscopic Cycle Technology (HCT) is a power cycle distinguished for using hygroscopic compounds-water mixtures as the working fluid to optimize the condensation process of the turbine exhaust steam by absorption phenomena. Previous works focused on the performance of the condensation/cooling section of the cycle as well as in the main improvements achieved by HCT in comparison to traditional thermal power generation cycles in terms of efficiency and profitability. Nevertheless, the thermodynamic characteristics of the steam generated from hygroscopic-water mixtures in the HCT boiler are yet to be studied. In this article, a theoretical analysis of temperature and pressure conditions of pure water steam generated from different concentrations of LiBr-water mixtures is carried out by using the Engineering Equation Solver (EES) software. Results show that LiBr-H₂O mixtures display higher saturation temperatures than pure water, which enables the cycle to directly generate superheated vapor with no need for superheating equipment inside the boiler. This fact further improves the economic advantages previously shown by HCT, since erection, operation and maintenance costs related to the superheating process are avoided.

Keywords

Hygroscopic cycle, lithium bromide, superheated steam.

1. Introduction

Despite the latest strategies followed by developed countries towards sustainable energies [1] [2], non-renewable sources still play a significant role in power generation. According to the 2020 global generation mix, fossil fuels were accountable for approximately 60% of the world's total electricity production, while nuclear and renewable energies were the source of the 40% remaining [3]. Due to the limited reserves and recent high increase in prices of the former, the improvement in generation processes conversion efficiency becomes key to fully take benefit from these non-renewable primary energy sources. In this way, research towards technically improving thermo-electrical power cycles has become a tendency due to its worldwide importance. As one of the most used

technologies, the Rankine cycle, despite its industrial maturity due to a widely spread exploitation for a vast set of processes along time, still becomes a target of most efforts to achieve greater effectiveness when transforming heat into work. Derived from its worldwide use, Rankine cycle efficiency marks a great impact on fuel consumption, greenhouse gases emissions and, ultimately, on the profitability of power plants [4].

The main methods developed to enhance the thermal efficiency of Rankine cycles are supercritical, reheated, regenerative and binary vapor cycles, which are mainly based on reducing losses due to irreversibilities. Furthermore, the prevention of vapor from entering the process pumps and keeping the quality of the steam at the turbine outlet above 90% are among other objectives of these approaches [5] [6].

The latest research trends lean towards introducing new working fluids instead of pure water for the enhancement of thermal efficiency. In this sense, the Organic Rankine Cycle (ORC), with a similar configuration to the typical Rankine cycle, is specifically designed for the conversion of low-grade heat into power, ranging from 80 to 400 °C [7]. ORC is differentiated for basing its operation on pure organic fluids such as refrigerants and other organic compounds [8], which can be defined as “dry” fluids, implying no superheating of the vapor is necessary. ORC manages competitive efficiencies while fluids work at much lower evaporation temperature and pressures than in traditional steam cycles [9].

Nevertheless, blends of liquids with different boiling points, known as zeotropic mixtures, are also suitable as working fluids for ORC, even so, few have been applied to this cycle in practical engineering, which implies uncertainty regarding its efficiency. In this way, multiple research efforts have been performed to compare both pure organic fluids and zeotropic mixtures regarding efficiency, concluding that the latter do not show better results except under specific process circumstances such as cooling water fixed temperatures. Nonetheless, these mixtures can still be considered due to environmental growing concerns

[10] [11]. Moreover, the ammonia-water combination poses a particular case of zeotropic mixtures being used in the Kalina cycle. When compared to pure organic ORC, its main competitor in terms of harnessing low heat sources. The former thermodynamic power cycle provides an additional degree of freedom in terms of mixture composition adjustment but a more complex configuration. Concerning efficiency, the Kalina cycle shows, generally, higher values than OCR due to less irreversibility [12], however, this statement is constrained by several factors such as OCR working fluid, process optimization and the number of heat stream sources [13] - [17].

Binary mixtures are also present in the Goswami cycle [18]. That cycle exploits the benefits offered by an ammonia-water mixture to generate power and provide cooling, preferably from mid-low-heat sources, by combining respectively a Rankine and an absorption refrigeration cycle [19]. Rankine cycle modifications also play a role in low-grade heat exploitation. In this sense, Chen et. al [20] evaluate the room for efficiency when reproducing supercritical conditions in this thermal cycle while using zeotropic mixtures as the working fluid, achieving an enhancement up to approximately 15% over the ORC.

The previously displayed thermodynamic power cycles face several challenges mainly derived from atmospheric and location site conditions. In this way, current climate tendencies have a deep influence on the efficiency of thermal cycles since higher ambient temperatures significantly decrease the refrigeration capacities of cooling processes. Furthermore, apart from the raised in global temperatures, locations with hot climates are not conducive to thermal cycles implementation [21].

Water scarcity also poses a restriction for the erection of power plants working on thermal power processes, indeed, a continuous and guaranteed source of water in power plants vicinities stands as an inevitable requirement to feed open refrigeration systems. This water shortage could be both caused by the increasing lack of precipitations due to climate change or already existing weather conditions intrinsic to the location, such as desertic areas. Thermal-electrical cycles water consumption optimization implies a great reduction in water withdrawal, for instance, worldwide power generation accounts for approximately

10% of total water consumption, primarily as cooling water [22].

In this sense, the named Hygroscopic Cycle Technology (HCT), conceived by researchers Rubio-Serrano et al. [6], [23], positions as a novel, cutting-edge proprietary thermodynamical power cycle, capable of improving and addressing debilities of the past cycles while confronting today and future technical challenges to enhance the overall efficiency of thermal cycles even further. Consequently, the HCT marks a new path in the conversion of heat to power by incorporating hygroscopic compounds [24] into the working fluid. In this way, the cooling process poses a key part of the cycle by optimizing the condensation of the steam exhausted by the turbine through absorption phenomena.

Nevertheless, these hygroscopic substances must fulfill several requirements to be suitable for the HCT [25]:

- High hygroscopic properties for strongly attracting water as vapor of liquid from the surroundings.
- Easy separable to ease the later desorption of vapor, achieving in final terms reversible retention.
- Less volatile than water (vapor pressure lower than pure water).
- Non-flammable
- Non-toxic
- Chemical stable at the cycle working conditions.

Rubio-Serrano et al. [26] proposed $LiBr-H_2O$ mixtures as the adequate working fluid for the HCT, a highly hygroscopic and soluble salt in all the operating conditions of the cycle. Furthermore, LiBr experiences a solubility increase in water as the solution temperature rises [27].

As seen in Fig.1, the HCT diagram initially follows the layout of the Rankine cycle incorporating a different cooling scheme based on the physical and chemical principles of absorption machines leading to several advantages towards efficiency, ambient adaptation and consumes respect to the latter.

Even so, HCT does show further improvements when compared to both Kalina and Goswami cycles while displaying fewer components.

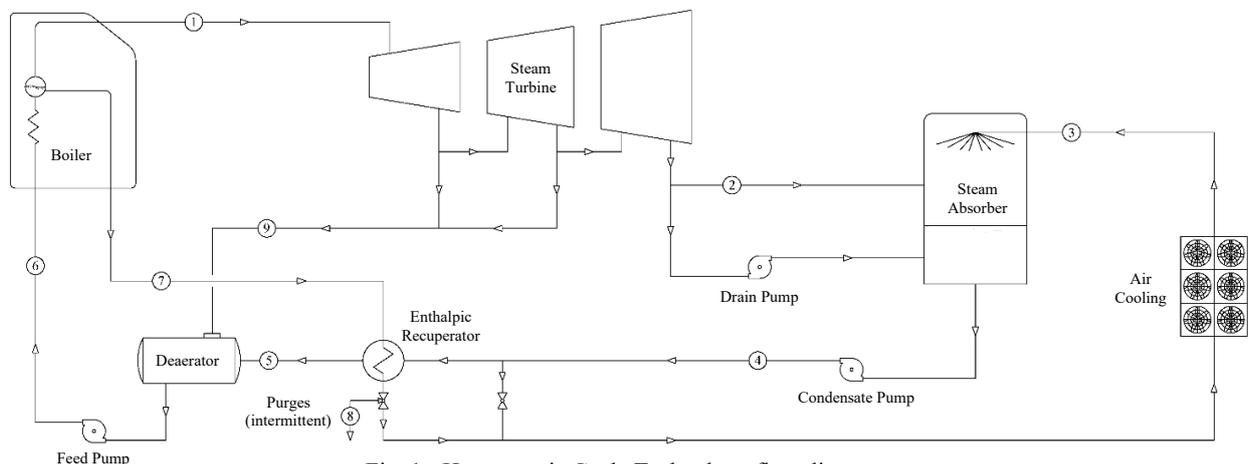


Fig. 1 - Hygroscopic Cycle Technology flow diagram.

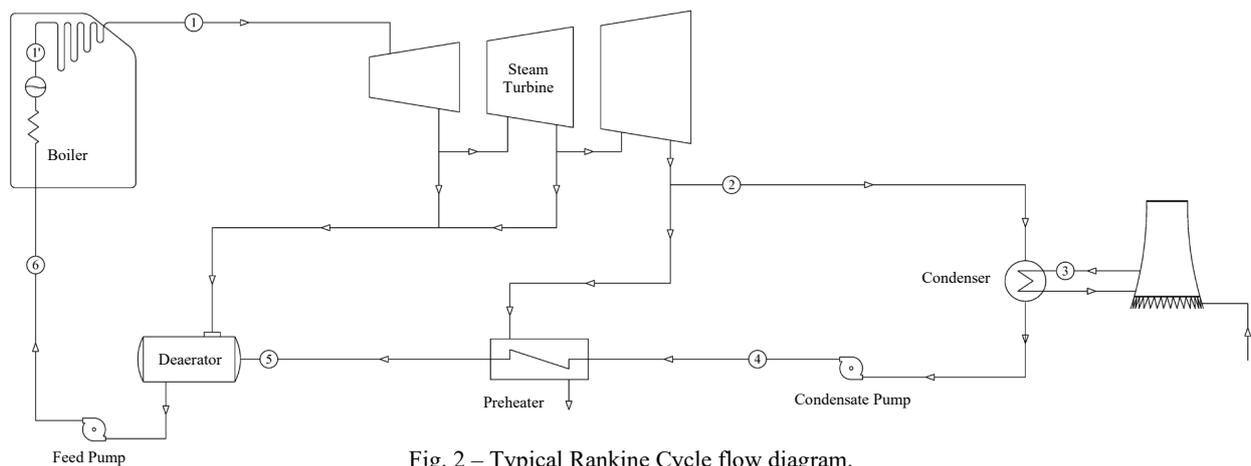


Fig. 2 – Typical Rankine Cycle flow diagram.

HCT capacity to adapt to any range of power generation while also not being limited to low-grade heat sources constitute some of these assets. In this way, HCT technology has already been successfully implemented in generation plants with powers ranging from 12,5 MW up to 50 MW [28]. Furthermore, the steam/hygroscopic compound separation does not require additional heat sources or special desorption equipment to be used [25]. HCT exhaust pure steam (Fig. 1, point 2) direct condensation is achieved by absorption when this current meets the hygroscopic compounds-water solution, which forms the cooling reflux stream (Fig. 1, point 3), inside the absorber. This key process results in two main advantages over other thermal cycles like Rankine [6], [29].

Firstly, a reduction of the condensing pressure for a given cooling temperature is achieved, effectively raising the electrical power output of the turbine as well as the overall electrical performance of the plant. Secondly, an increment on the condensing temperature for a given condensing pressure is accomplished, consequently raising the cooling temperature. As a result, the condensation energy can be dissipated in dry mode (air-cooler), instead of using typical open cooling processes, such as cooling towers, leading to substantial benefits like savings in water consumption [30], tower purges, plumes as well as operation and maintenance costs. The increased condensing temperature also implies a reduction in the heat energy that must be dissipated by the air-coolers, allowing to also raise the overall electrical efficiency of the plant due to a lower power demand of the cooling system [31]. Furthermore, air-coolers offer the chance to strictly control the reflux water refrigeration process by regulating the speed of fans according to the ambient temperature. Therefore, the high performance of the HCT is evident in several improvements which further enhance the thermal to power conversion, as a direct consequence of the new cooling process integrated into this technology [5]:

- New cooling conditions are translated into a higher annual production due to a lower turbine outlet pressure.
- Lower dependency on water and ambient conditions such as high temperatures allow extending the availability of power plants operating with HCT.
- Lower electric auto-consumption.
- Overall increment of the electrical efficiency ($\approx 2,5\%$).

In this way, HCT is a technology able to replace and further improve the Rankine cycle for any heat to power conversion in different types of electric generation plants, such as combined cycles, thermoelectric plants, biomass power plants and nuclear power plants [29]. HCT shows several improvements such as [5]:

- Savings up to 50% regarding consumption of demineralized water and chemical additives.
- Costs related to investment and O&M are reduced by 5% and 25% respectively.
- Longer service life while increasing reliability and availability.

However, a key process that has not yet been studied in detail is the steam generation in the boiler of the HCT, nor the thermodynamic characteristics of the steam generated at different hygroscopic compound concentrations.

2. Objective

As previously presented, Rubio-Serrano et al. [25] [26], studied the benefits and overall performance of hygroscopic mixtures, specifically for different concentrations of lithium bromide-water along the cooling process of the Hygroscopic Cycle, showing significant improvements with respect to the traditional Rankine cycle. However, these efforts were mainly focused on the cooling section of the HCT. In this way, the main objective of this paper is to further analyse the thermodynamical evolution and behaviour of *LiBr* mixtures along the heating process to compare pure water steam conditions coming from both *LiBr-H₂O* mixtures and pure liquid water at the same pressures to properly identify potential benefits of the former during the vapor generation step with respect to typical Rankine cycles. Boiler configurations for both HCT and Rankine cycle are shown in Figs. 1 and 2 respectively. The removal of superheater equipment, extensively used in the former, emerges as an opportunity when operating an HCT with a *LiBr-H₂O* mixture as the working fluid. This statement stems from *LiBr-H₂O* mixtures potentially showing higher saturation temperatures than pure water at the same pressure. This *LiBr-H₂O* saturated state offers the chance to directly generate pure superheated steam from this hygroscopic dragged due to the nature of the vaporization process, remaining dissolved in the liquid fraction.

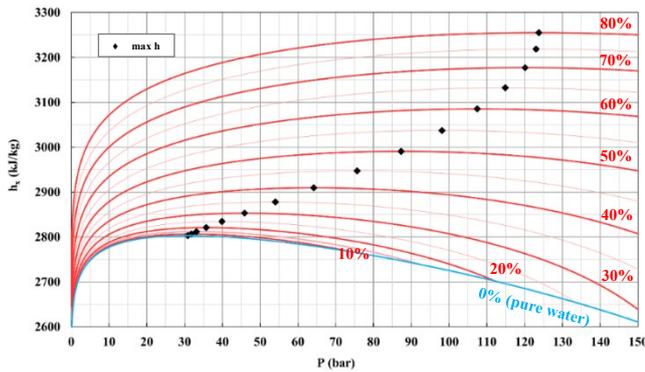


Fig. 3 - Enthalpy (h_x) as a function of concentration (c) and saturation temperature (T_{sat}).

For this purpose, saturation temperatures for $LiBr-H_2O$ and water have been determined for further comparison.

In addition, an optimization calculus of the boiler conditions, for each studied $LiBr$ concentration, has been developed to determine the best working point at which steam enthalpy is maximized with the goal of increasing the performance of the turbine.

3. Methodology

EES is an abbreviation for Engineering Equation Solver, being this software capable of solving both coupled non-linear algebraic and differential equations, EES's high capacity and accuracy regarding thermodynamic functions computation is the main reason behind its selection for the calculations performed along with this research.

Values for thermal characteristics of $LiBr-H_2O$ mixtures reflected in this article have been obtained by simulating $LiBr$ conditions according to property routines and databases [32] [33] included in EES software (version 10.833-3D).

The limits analysed for each attribute have been established according to standard operating conditions of the HCT on Table 1.

Table 1. Limits for evaluated HCT operating conditions.

Property	Range
Pressure (bar)	0 - 150
Concentration (%)	0 - 80

Saturation temperature (T_{sat}) for both pure water and $LiBr-H_2O$ have been determined in EES as functions of concentration (c) and/or pressure (P) (Equations 1 and 2):

$$T_{sat_{H_2O}} = f_1(P) \quad (1)$$

$$T_{sat_{LiBr-H_2O}} = f_2(P, c) \quad (2)$$

Furthermore, enthalpy of the saturated vapor (Fig. 2a, point 1') is a function of the boiler pressure (P) and corresponds to a quality (x) equal to 1 (Equation 3).

$$h_{1'} = f_3(P, x); x = 1 \quad (3)$$

In addition, enthalpy of the superheated vapor (Fig. 2, point 1) is a function of the boiler pressure (P) and the saturation temperature of the mixture ($T_{sat_{LiBr-H_2O}}$) at the concentration (c) considered (Equation 4).

$$h_1 = f_4(P, T_{sat_{LiBr-H_2O}}) \quad (4)$$

4. Results and analysis

In Fig. 3, pure steam enthalpies for vapor generated from both $LiBr-H_2O$ mixtures (h_i) and pure water ($h_{i'}$) have been determined as a function of $LiBr$ concentration and pressure by using EES.

Simulated results confirm that enthalpies of vapor produced by $LiBr-H_2O$ mixtures are higher than those of pure water at the same pressure.

Consequently, steam generated from the former is directly located in the superheated steam region. The difference between the enthalpies mentioned increases with pressure levels, being more significant at high concentrations (c) and pressures (P).

An enthalpy optimization has also been carried out to determine the most favourable HTC operating conditions for each $LiBr$ concentration to reach the highest possible steam enthalpy. These specific points allow to maximize the power output due to a greater enthalpy change in the turbine and thus the energy efficiency of the cycle.

Phenomena described in Fig. 3 is further evidenced by Fig. 4, where the maximum enthalpies (h_i) at the different concentrations (corresponding to superheated vapor) are compared to the enthalpies of the saturated vapor ($h_{i'}$) for pressures ranging from 30 to 130 bar. Thus, optimized enthalpies from superheated vapor show the maximum difference (Δh) achieved when $LiBr-H_2O$ mixtures are used instead of pure water as the working fluid.

Fig. 5 shows the gap (ΔT) between saturation temperatures of $LiBr-H_2O$ mixtures (T_i) and pure water ($T_{i'}$) as a function of concentration (c) and pressure (P). Therefore, temperature results back-up the behaviour observed in enthalpies.

Finally, Table 2 quantitatively represents the enthalpy and temperature increases between HCT and Rankine cycle, graphically shown in Fig. 3, Fig. 4 and Fig. 5. Therefore, HCT can directly produce superheated steam without using a superheating phase inside the boiler.

Δh and ΔT represent the increment in enthalpy and temperature that boiler must provide in the Rankine cycle to reach the same conditions for the steam, directly obtained in HCT.

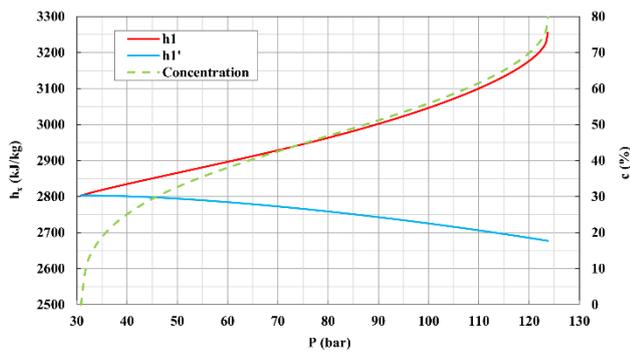


Fig. 4 – Enthalpy optimization for the boiler outlet as a function of *LiBr* concentration (*c*) and pressure (*P*).

Table 2. Optimized pressure, enthalpy and temperature differences versus *LiBr* concentration.

Concentration (%)	Pressure (bar)	Δh (kJ/kg)	ΔT (°C)
0	30.82	0.0000	0.00
5	31.48	0.9035	0.26
10	31.79	3.4963	0.96
15	33.16	9.0209	2.46
20	35.76	18.5506	5.00
25	39.88	33.5397	8.88
30	45.88	55.8467	14.43
35	54.04	87.5074	21.92
40	64.22	129.9306	31.47
45	75.67	182.7635	42.96
50	87.32	243.5708	56.04
55	98.16	308.6477	70.23
60	107.49	374.0261	85.03
65	114.89	436.0963	99.89
70	120.09	491.9418	114.33
75	123.03	539.5681	128.00
80	123.76	577.9903	140.64

5. Conclusions

HCT positions as a novel cycle capable of overcoming limitations previously established in past thermodynamic power technologies by introducing key improvements to enhance the overall performance and profitability. These advantages are evidenced by a reduction in O&M and investments costs as well as water consumption, and an extension of the service life of the plant as shown in the literature.

To further expand HCT benefits, thermodynamic simulations performed in this article through EES software reflect the differences in between thermodynamic characteristics of *LiBr-H₂O* mixtures and pure water. Vapor enthalpies and temperatures obtained for the former at saturation conditions and different *LiBr* concentrations are consistently higher than values presented by the pure water at the same pressure levels.

In this sense, the quantity of this salt in the mixture plays a significant role while evaluating those differences. In fact,

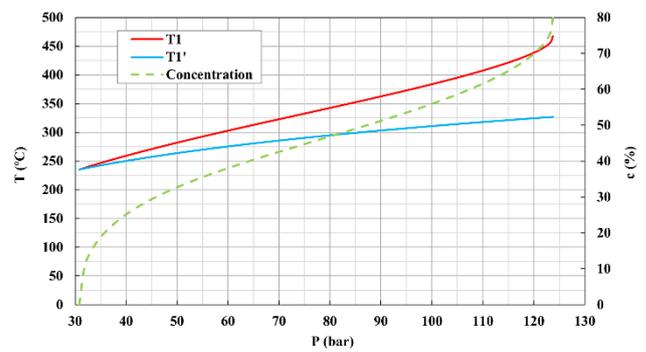


Fig. 5 – Saturation temperature of *LiBr-H₂O* mixtures and pure water as a function of concentration (*c*) and pressure (*P*).

temperature and enthalpy increments further rise as concentrations and pressure levels increase.

These results may be used to find the most convenient operating conditions in the boiler for increasing the cycle efficiency over the values of 2,5% reported in the literature and will be considered for future studies.

Additionally, the enthalpy values of *LiBr-H₂O* mixtures at saturation conditions ensure the generation of superheated vapor with no need for further heating. Therefore, it can be concluded that HCT does not require any superheater inside the boiler, unlike the Rankine cycle.

Avoiding the need of a superheater has several impacts which, in final terms, reinforce the advantages of HCT over other thermodynamic power generation cycles. In this case both economic and technical aspects of the HCT are improved since costs related to the erection, operation and maintenance of this equipment are eliminated. Furthermore, pressure losses from the boiler to the turbine are lowered since steam must travel shorter distances, effectively reducing friction against pipe walls.

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