

Analytical study of the absorber performance of a Hygroscopic cycle for low concentrations of LiBr solutions

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Abstract.

Nowadays, higher ambient temperatures and water scarcity, primarily due to climate change, represent a challenge for the refrigeration systems of traditional thermodynamic power cycles. The novel Hygroscopic Cycle Technology arises as a solution to mitigate those drawbacks by means of hygroscopic compounds, which lead to a condensation process by absorption in a mixing chamber, called absorber. Consequently, heat rejection can be achieved at higher cold sink temperatures in a closed loop, avoiding water consumption. In this work, the influence of the concentration of the hygroscopic salt LiBr in the condensation process inside the absorber, key element of the cycle, has been analyzed with EES software. The analysis is divided into very low (0% to 0.01%) and low (0.01% to 5%) concentrations of LiBr-H₂O solutions. Absolute pressure at the absorber ranges between 3 kPa and 21 kPa. Results show that properties of very low concentration mixtures can be approximated to those of pure water, showing errors lower than 0.11%. As concentration rises from 0.01 to 5 % specific enthalpy decreases, leading to lower consumption of the refrigeration system of the cycle.

Key words. HCT, absorber, hygroscopic compounds, concentration.

Nomenclature

c_c :	LiBr concentration of the condensate.
c_r :	LiBr concentration of the cooling reflux
h_c :	enthalpy of the condensate
h_r :	enthalpy of the cooling reflux
h_v :	enthalpy of the exhaust steam
h_w :	enthalpy of water
\dot{m}_c :	mass flow rate of the condensate.

\dot{m}_r :	mass flow rate of the cooling reflux
\dot{m}_v :	mass flow rate of the exhaust steam
T_c :	condensing temperature
T_r :	temperature of the cooling reflux
T_v :	temperature of the steam
ϕ_r :	dimensionless cooling reflux
ϕ_v :	dimensionless steam flow rate

1. Introduction

Today, the use of fossil fuels still accounts for 80% of the primary energy used by power plants [1]. The most widely used system is the Rankine (or steam turbine) cycle, applied in traditional power plants. This highlights the impact that an improvement in the efficiency of Rankine cycles can have on the planet, both in terms of reducing primary energy consumption and pollutant emissions into the atmosphere. The application of the Rankine cycle to renewable energy sources has once again boosted the number of research projects in this field. Among the proposed improvements that are gaining momentum in the current literature is the use of fluids more volatile than water for medium and low temperature applications (such as organic Rankine cycles, or inorganic ones such as Kalina or Goswami). With the development of a new technology called the hygroscopic cycle in 2010, there is the possibility to improve the traditional Rankine cycle by introducing an absorber with hygroscopic compounds [2]. These compounds have a high affinity with water vapor (deliquescent materials), so they are able to capture or absorb the steam coming from the turbine. This system can reduce the expansion pressure and increase the energy production in the turbine, while reducing the size of the

condenser, the major economic barrier to obtaining viable Rankine cycles in applications with renewable thermal sources [3]. In this way, the energy efficiency of the system can be improved, and its investment cost can be reduced, while the dependence on the cold sink temperature of the refrigeration system is considerably reduced. In addition, the use of the absorber eliminates the need for cooling water.

The benefits of applying this technology have been proven in a 12.5 MW "Vetejar" biomass power plant located in Palenciana (Córdoba-Spain) [4], which is capable of increasing the condensing temperature, with an average annual efficiency improvement of 2.5%. Within the hygroscopic cycle technology, the equipment called the absorber consists of a mixing chamber where the steam flow coming from the turbine arrives and a recirculated water flow carrying a hygroscopic compound (cold solution) are mixed (Fig. 1). In the absorber the steam is condensed by means of an absorption process.

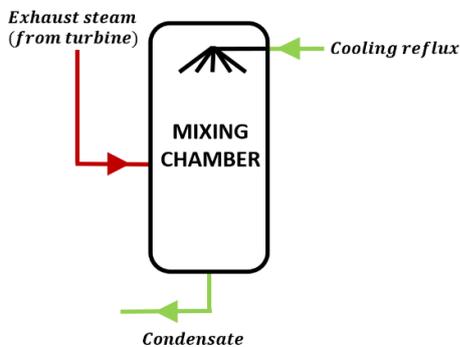


Fig. 1. Mixing chamber

Currently, there is a great lack of knowledge about the particularities of this absorption condensation, both at the level of fluid dynamics and the thermochemical process that takes place. On the other hand, it has been observed that the same process used for the absorption of steam by the hygroscopic compound can be extrapolated to multiple applications involving the interaction and mixing of steam and hygroscopic particles.

Specifically, the objective of this paper is to develop an analysis of the main variables involved in the process of absorption and to set a relationship between them. When working with hygroscopic fluids, the concentration of the salts plays a crucial role in the absorption process. High LiBr concentrations have been studied (45 – 65%) [3], nevertheless, these LiBr levels required further technical considerations in order to guarantee the correct performance of the cycle. In this sense, lower concentrations are yet to be studied. The analysis is divided into two parts: one corresponding to a very low concentration of the hygroscopic salts study (rated between 0% and 0,01%) and the other to a low concentration study (between 0,01% and 5%). These two studies are carried out at different pressures at the absorber. The results of the project would contribute to a better understanding of the phenomena taking place in the absorber in order to set the basis for a high-concentration analysis, which is the next step to take in the HCT.

2. Methodology

The methodology of this project is based on the development of an analytical model of the absorber in order to perform several parametric analyses of the variables involved in the condensation of the steam. The hygroscopic salt used is LiBr. The concentration of the salt is varied between 0% and 5 %. Absolute pressure at the absorber is varied between 3 kPa to 21 kPa.

To perform the study software EES [5] is used. It has been chosen mainly because of the long experience with the programme, its extensive thermodynamic database (including a library of the properties of LiBr solution) and for all the analysis possibilities it offers (graphs, parametric analysis, implementation of functions, etc.).

Eq (1) to (3) present mass, energy and concentration balance at steady flow conditions in the absorber.

$$\dot{m}_v + \dot{m}_r = \dot{m}_c \quad (1)$$

$$\dot{m}_v \cdot h_v + \dot{m}_r \cdot h_r = \dot{m}_c \cdot h_c \quad (2)$$

$$\dot{m}_r \cdot c_r = \dot{m}_c \cdot c_c \quad (3)$$

Mass flow rates are presented as dimensionless magnitudes in eq. (4) to (6). Dimensionless steam flow rate and dimensionless cooling reflux flow are defined as in eq. (7) and eq. (8).

$$\phi_v + \phi_r = 1 \quad (4)$$

$$\phi_v \cdot h_v + \phi_r \cdot h_r = h_c \quad (5)$$

$$\phi_r \cdot c_r = c_c \quad (6)$$

$$\phi_v = \frac{\dot{m}_v}{\dot{m}_c} \quad (7)$$

$$\phi_r = \frac{\dot{m}_r}{\dot{m}_c} \quad (8)$$

Temperatures of the steam and of the cooling reflux are related to the temperature of the condensate as presented in eq. (9) to (10).

$$T_v = T_c + 2 \quad (9)$$

$$T_r = T_c - 7 \quad (10)$$

The exhaust steam enters the absorber as superheated. The difference between T_r and T_c is seven degrees Celsius due to design parameters.

3. Results

Results for low concentration analysis are presented in Table 1. For concentrations between 0% and 0.01% enthalpy of the condensates hardly varies with concentration. In Table 1, mean values of the condensate enthalpy and its standard deviation are shown. When operating in this range of concentrations, the enthalpy of the condensate (with hygroscopic compounds) and enthalpy of saturated water at T_c differ by less than 0.11%.

Therefore, it is acceptable to approximate the enthalpy of hygroscopic dissolution by that of the water. This result has been, previously, proven in the pilot plant [6].

Table 1. Results for low concentration analysis

Pressure (kPa)	T _c (°C)	Mean h _c (kJ/kg)	Standard deviation of h _c (kJ/kg)	Water enthalpy (h _w) (kJ/kg)	Relative error (%)
3	24.08	100.89	0.057	101.00	0.109
6	36.16	151.38	0.063	151.50	0.079
9	43.76	183.18	0.063	183.30	0.065
12	49.43	206.78	0.063	206.90	0.058
15	53.97	225.85	0.053	225.90	0.022
18	57.80	241.88	0.063	242.00	0.050
21	61.12	255.86	0.052	255.90	0.016

The dimensionless mass flow of the cooling reflux (and, consequently, the dimensionless mass flow of the exhaust steam) does not vary when changing the concentration of hygroscopic compounds and shows almost no variation when increasing the condensate pressure. Mean dimensionless mass flow of the cooling reflux and steam for low concentration are presented in Table 2.

Table 2. Dimensionless mass flows

	Mean	Standard deviation
ϕ_r	0.988	0.00018
ϕ_v	0.012	0.00017

The concentration of the cooling reflux does not vary with pressure, as can be seen in Fig. 2. The concentration of the cooling reflux increases linearly with the concentration of the condensate, as expected.

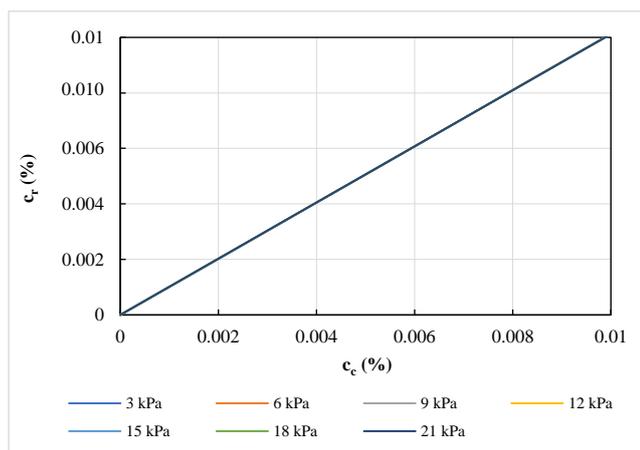


Fig. 2. Variation of the concentration of the cooling reflux with the concentration of the condensate for different pressures.

Fig. 3 to Fig. 6 show the results obtained for the low concentration (0.01% to 5%) analysis. Dimensionless mass flow of the cooling reflux (Fig. 3) increases almost linearly with the concentration of the condensate, the higher the concentration the more mass flow of the cooling reflux is

needed to condensate the steam. The absorber is able to work with high vacuum, but with low pressures more mass flow of the cooling reflux is required to produce the condensation.

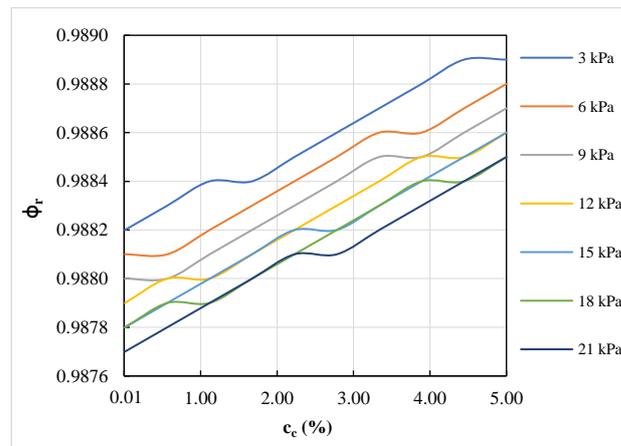


Fig. 3. Variation of the dimensionless mass flow of the cooling reflux with the concentration of the condensate for different pressures.

As described in the very low concentration analysis, concentration of the cooling reflux presents a linear relation with the concentration of the condensate. Pressure does not affect the value of the cooling reflux concentration.

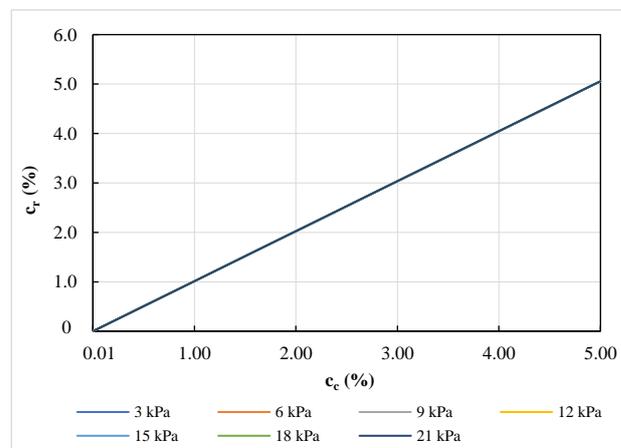


Fig. 4. Variation of the cooling reflux concentration with the concentration of the condensate for different pressures

In contrast with the very low case, for low concentration the condensing temperature changes with the concentration of the condensate (Fig. 5). However, it is not a considerable variation. More noticeable is the increase of the condensing temperature with the increase of the condensing pressure. Condensing temperature is different from the saturated temperature of the water, due to the effect of the salts.

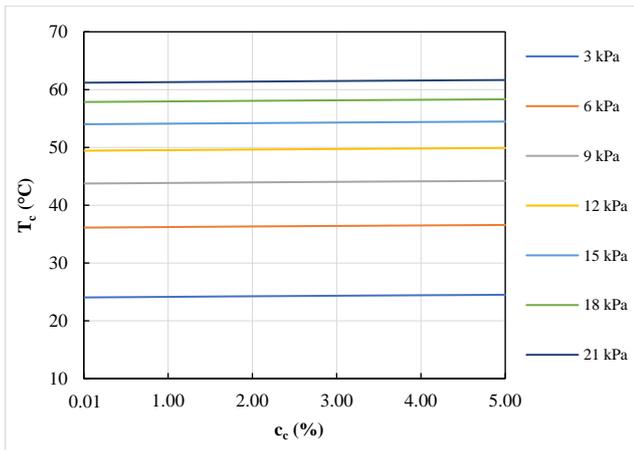


Fig. 5. Variation of the condensing temperature with the concentration of the condensate for different pressures.

When working with low concentration, the enthalpy of the condensate varies considerably with the concentration (Fig. 6). At these levels, enthalpy decreases with the concentration. Due to a lower value of the enthalpy of the condensate, the energy to dissipate at the dry-coolers is decreased, and, therefore, its consumption is also decreased, however, it has been tested at the pilot plant that the efficiency of the system does not improve noticeably than when working with very low concentrations.

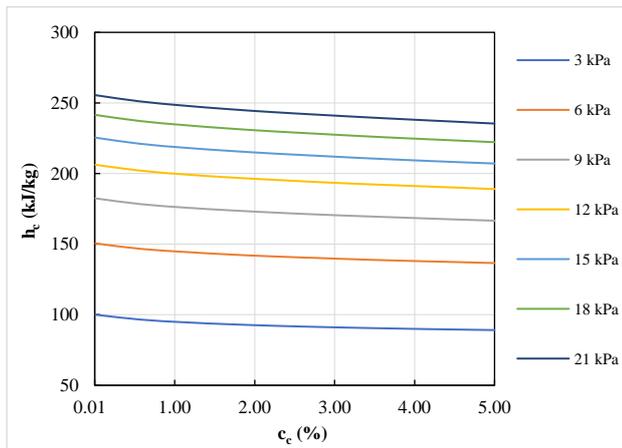


Fig. 6. Variation of the enthalpy of the condensate with the concentration of the condensate for different pressures

4. Conclusion

The absorption process has a high relevance in the correct operation of the Hygroscopic Cycle Technology. In this work, an analytical study of the main variables that influence the absorption process has been performed. The results have allowed establishing relationships between these variables, with the concentration of hygroscopic salts playing a crucial role.

Two different behaviors were observed as a function of salt concentration. Between 0 and 0.01% (very low concentration), mixture properties were very similar to the properties of pure water. With relative errors lower than 0.11%, it may be reasonable to use pure water as the

modeling fluid. For low concentrations (0.01 to 5%), this assumption may lead to high errors in modeling.

Regarding the concentration of the cooling reflux, a linear relationship with the condensate concentration was found, independently of the condensing pressure. Nevertheless, the mass flow of the cooling reflux was found to rise as the concentration is increased. Furthermore, enthalpy values of the condensate decrease as the concentration rises from 0.01 to 5%, leading to lower consumption of the heat rejection system of the cycle.

Future works may include analyzing higher salt concentrations while performing tests in an experimental absorber demonstrator. Another interesting option could be the testing of salts with different thermophysical properties.

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