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ENERGY AND EXERGY ANALYSIS OF A ADSORPTION CHILLER

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Abstract. *This paper shows the energy and exergy analysis of a two-bed adsorption chiller. The system was developed at LES/CEAR/UFPB, and constitutes of two adsorption reactors, a condenser and an evaporator, which function independently. Cycle times and secondary flow switching control scheduling is performed using a LabVIEW® interface that allows automatically secondary flow control through the cycle management system (SGC). The experimental tests were performed with the silica gel / water adsorptive pair. The specific cooling capacity (SCP) and coefficient of performance (COP) of the two-reactor chiller were 81.4 W kg^{-1} and 0.52 respectively, with an exergetic efficiency of 8.2% for the best working conditions, represented by the triplet 72/30/15 °C and a cycle time of 35 min. The results reached the levels of recent publications of literature describing models with the same characteristics. The maximum temperature required for the operation of this system is compatible with the use of low-temperature industrial thermal waste and flat type solar collectors, which may allow its production on a commercial scale.*

Keywords: *adsorption chiller, energy and exergy analysis, solar energy*

1. INTRODUCTION

The air conditioner is recognized as a vital means for sustainability, due to its importance to meet the fundamental human needs, but the vapor compression systems, are mainly related to the choice of refrigerants, that generate some environmental impacts, such as emissions of greenhouse gases (*GHG*); depletion of the ozone layer and high consumption of electricity (UNEP, 2015).

Within the relevant environmental aspects, there are the main, unsustainable fluids used in the refrigeration by vapor compression, such as HCFCs, HFCs and, in particular, CFCs which, when released to the atmosphere, cause the greenhouse effect and degrade the ozone layer that protects our planet from harmful UV radiation, quantified by ODP (Ozone Depletion Potential) and GWP (Global Warming Potential) indicators. According to the report of the World Meteorological Organization (WMO) and the United Nations Environment Programme (UNEP), hydrofluorocarbons are one of the major greenhouse-gas-emitting agents and have a long life in the atmosphere, becoming the most aggravating problem of global climate change (Metz et al., 2007). At this moment of uncertainty regarding the national energy matrix and the risks of climate change caused by anthropogenic actions, the challenge is the development of alternative systems that can provide thermal comfort, environmentally sustainable, with low energy consumption or, even, reduction of consumption during peak hours, and the correct use of air conditioning and refrigeration systems, which are directly linked to the growth of society's economy and quality of life.

Thus, faced with these scenarios, the development of new alternatives that can contribute to solve these problems, such as the two-bed adsorption chiller, proposed in this paper, can progress as a strategic and economically feasible alternative for air conditioning purposes, since it is capable of harnessing the thermal energy of low temperature (60 ~ 90 °C) to regenerate the system, which is compatible with the use of flat-type solar collectors or residual heat from thermal waste, usually wasted in industrial processes or hybrid systems. (Leite et al., 2007; Vodianitskaia et al., 2017). But also because they are more environmentally friendly in terms of refrigerant use and energy demand (Luo et al., 2006; Riffel et al., 2010). Therefore, the researches on systems using this silica gel / water pair on the prospect of achieving better performance (Rezk, 2012; Mitra et al., 2015), ranging from commercial chillers to systems with advanced cascade cycles, with COP values of up to 1.1 (Uyun et al., 2009). Recently, an adsorption refrigeration system was investigated considering the energy and exergy analysis, and it was found an overall exergetic efficiency of 4.5% (LI, G. et al., 2014). The present work aims to determine the exergetic efficiency of a two-bed adsorption chiller, as well as two identify the cumulated destroyed exergy in each component of the two-bed chiller for a cycle of 35 min.

2. THEORETICAL FUNDAMENTALS

The ideal refrigeration cycle by adsorption consists of two isosteric processes (constant concentration) and two isobaric processes, equivalent to the evaporator and condenser pressures, shown in Figure 1. The processes within the two-reactor system are described in Table 1.

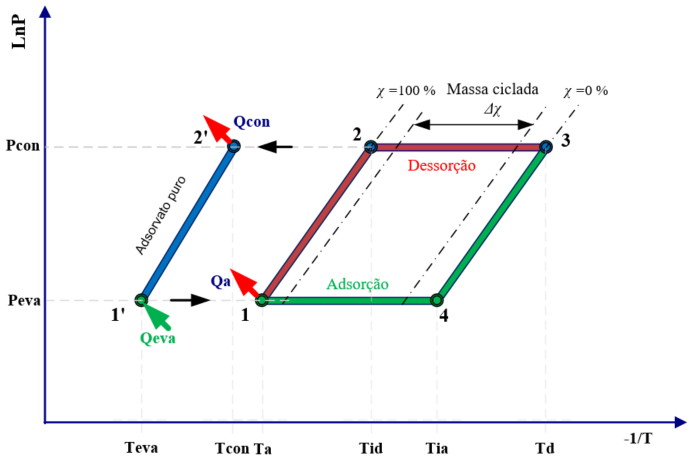

Figure 1. Ideal refrigeration cycle by adsorption- Clausius-*Clapeyron*.

Table 1 – Summary of adsorption cycle processes in the two-bed *chiller*.

Adsorptive reactor 1		**Adsorptive reactor 2**	
Processes	Description	Processes	Description
1~2	Isosteric preheating process	3~4	Isosteric precooling process
2~3	Isobaric heating process - desorption / condensation	4~1	Isobaric cooling process - evaporation / adsorption
3~4	Isosteric precooling process	1~2	Isosteric preheating process
4~1	Isobaric cooling process - evaporation / adsorption	2~3	Isobaric heating process - desorption / condensation

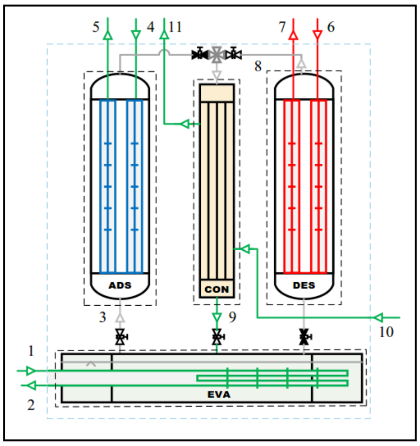

Figure 2. Mass and energy flow diagram of an adsorption two-bed chiller

Figure 2 above is a simplified operating diagram of the two-bed chiller with identification of the mass flow control points in each component of the system, for both the main and the secondary fluid, with the two reactors running simultaneously, one in the adsorption process and the other in the desorption process.

2.1 Energy and exergy balance of an adsorption refrigeration system

Considering a steady state and the following simplifying assumptions: (a) there is no heat exchange of any component with the neighborhood; (b) the effects of kinetic and potential energy can be negligible; (c) the overall heat transfer coefficients constant throughout the process, the energy balance of the adsorbing chiller is calculated, based on the principles of mass conservation and energy, expressed by the respective Eq. (1) and Eq. (2).

$$\frac{d\dot{m}}{dt} = \sum_{e} \dot{m} - \sum_{s} \dot{m} \tag{1}$$

$$\frac{d\dot{E}}{dt} = \dot{Q} - \dot{W} + \sum_{e} \dot{m}\, h - \sum_{s} \dot{m}\, h \tag{2}$$

By the first law of thermodynamics, the total energy balance for a closed system is determined by the sum of the net energy of the system, that is, it is the amount of energy supplied minus the energy rejected by the system during the interval considered in the analysis, $\Delta E = Q_{FOR} - Q_{REJ}$. However, for the adsorption refrigeration system, illustrated in Figure 3, it is defined by Eq. (3), which is calculated by the difference between the energy supplied to the system and the energy removed from the system during the process.

$$\Delta E = (Q_d + Q_e) - (Q_a + Q_c) \tag{3}$$

From the energy balance of adsorptive chiller for adiabatic processes, the difference between the desorption heat transfer, Q_d, and the heat rejected in the condenser, Q_c, is equal to the thermal work, W_t, necessary to move energy from the cold source, Q_e, and reject it in the intermediary source, which is the overall heat of the adsorption process, Q_a, determined by Eq. (4). Therefore, the cooling capacity generated by the adsorption cooling system is determined by the difference between the heat rejected by the reactor during the adsorption process and the thermal work supplied to the reactor during this process, expressed by Eq. (5).

$$W_t = Q_d - Q_c \tag{4}$$

$$Q_e = Q_a - W_t \tag{5}$$

According to Moran et al, (2011), exergy is the maximum possible theoretical work to be obtained from a global system, composed of a system and the environment, until the system reaches the reference state. The exergy can be generated by heat, work and mass flow, as described below.

The exergy of a heat flux is expressed as the maximum amount of useful work that can be generated from that heat flux and is defined by the Carnot efficiency of a heat engine working between the reference source and the reference state (6) and (7), and their difference determines the dispersed exergy as shown in Eq. (8).

$$Ex_q = \left(1 - \frac{T_0}{T_q}\right) Q_b \tag{6}$$

$$Ex_{\mathrm{f}} = \left(1 - \frac{T_0}{T_{\mathrm{f}}}\right) Q_b \tag{7}$$

$$Ex_{\mathrm{dest}} = Ex_q - Ex_{\mathrm{f}} \tag{8}$$

The work exergy, when there is no displacement of the system boundaries, is equivalent to the work itself, that is, $Ex_w = W$. As for the mass flow, its exergy is determined by the product of the mass flow and its specific exergy, defined by Eq. (9).

$$Ex_{mass\ flow} = \dot{m}\, e_x \tag{9}$$

With regard to the specific energy, e_x, When the kinetic, chemical and potential energy are disregarded it's determined by Eq. (10).

$$e_x = (h - h_0) - T_0(s - s_0) \tag{10}$$

The exergy inventory for an open system, considering the previous simplifying hypotheses and without deformation at the boundary of the system, at a steady flow, is defined by Eq. (11).

$$\sum \left(1 - \frac{T_0}{T_b}\right) \dot{Q}_b - \dot{W} + \left(\sum_e \dot{m}\, e_x - \sum_s \dot{m}\, e_x\right) - Ex_{\text{dest}} = 0 \tag{11}$$

2.2 Performance indicators

COP (coefficient of performance) and SCP (specific cooling power) are usually the indicators used to measure the performance of the adsorption refrigeration system. However, these analyzes do not consider all the parameters that are vital for the performance evaluation of an adsorption refrigeration system. Therefore, efficiency and exergy analyzes can assess efficacy and play a complementary role in assessing such systems.

In this thesis, the overall performance of an adsorption chiller was evaluated, with respect to each parameter of the system, the conventional indicators, COP and SCP, which are defined by Eq. (12) and Eq. (13), respectively.

$$COP = \frac{\dot{Q}_e}{\dot{Q}_d} = \frac{\dot{m}_2 \cdot h_{vl}}{\dot{Q}_{12} + \dot{Q}_{23}} = \frac{\dot{m}_{eva}\left(h_{eva,e} - h_{eva,s}\right)}{\dot{m}_{des}\left(h_{des,e} - h_{des,s}\right)} \tag{12}$$

$$SCP = \frac{\dot{Q}_e}{\dot{m}_a} \tag{13}$$

In addition to these indicators, we evaluated the exergetic efficiency, also referred to as second law or rational efficiency, defined as the ratio between the thermal efficiency of a real cycle and the efficiency of the reversible cycle operating between the same temperatures. For a cooling cycle, it is determined by the relation between the actual and Carnot cycle performance coefficients, according to Eq. (14).

$$\eta_{ex} = \frac{COP}{COP_{Carnot}} \tag{14}$$

According to Rezk and Al-Dadah (2012), the Carnot coefficient for an adsorption cooling system is defined by Eq. (15).

$$COP_{\text{Carnot}} = \left(1 - \frac{T_{con}}{T_{reg}}\right)\left(\frac{T_{eva}}{T_{ads} - T_{eva}}\right) \tag{15}$$

3. EXPERIMENTAL PROCEDURE

In order to carry out the experimental evaluation, a two-bed chiller was developed, in full laboratory scale, using silica gel / water pair and composed of four main parts, shown in Figure 4a, two adsorbent reactors with a heat exchanger with four finned tubes, grouped in parallel; a condenser, concentric tube type with countercurrent flow, using as cooling fluid water at room temperature; an evaporator, with cascade-sprinkled fluid, forming a water film in helical form on a copper heat exchanger. Figure 4b is an exploded view of the major components of the system.

The system was previously evacuated with the use of a vacuum pump and the control and monitoring systems are then connected. To maintain the temperatures in the ranges previously programmed for the reactors and evaporator, the temperatures and the mass flow of the secondary fluid are controlled. The condenser is cooled with water directly from the supply system at room temperature. The cycle scheduling is performed by the cycle management system (CMS). Considering the results presented by (Li et al 2014; Vodianitskaia et al., 2017) and the results of the characterization of the system, the cycle times evaluated were previously maintained in the range of 30 to 50 minutes and the execution was performed according to the experimental design.

To carry out the monitoring of the secondary fluid flow and control cycle times, a cycle management system (CMS) was developed, using a LabVIEW® interface that allows control of the secondary flow through scheduling of cycle times and secondary flow switching control of the parameters required to perform the energy and exegetical analysis and quantify the performance indicators of said adsorption chiller.

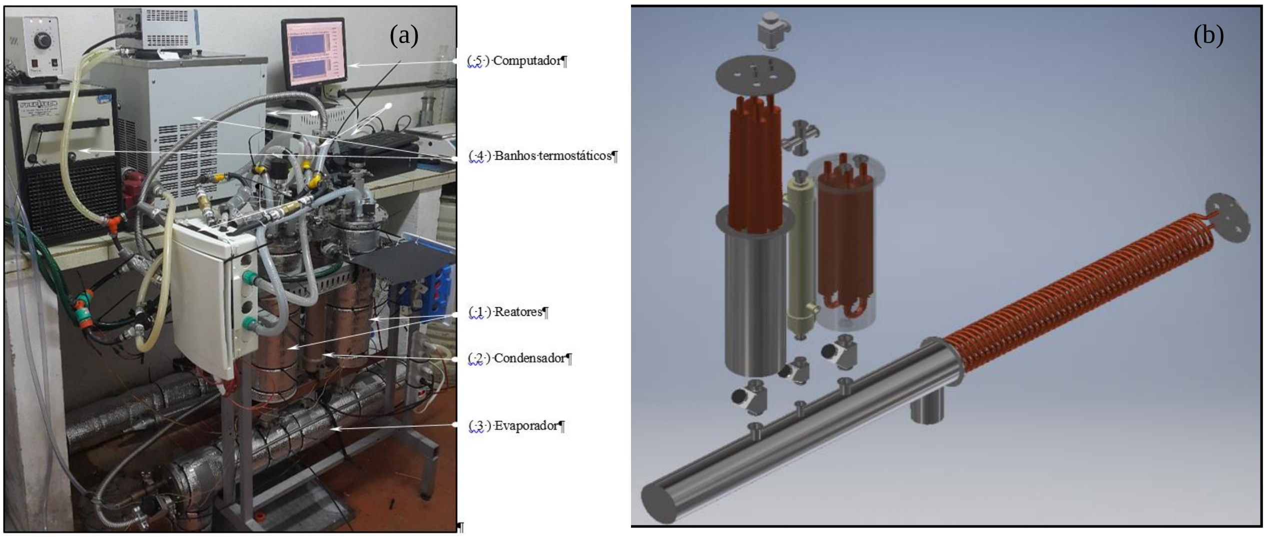

Figure 4. a. Experimental Two-bed Chiller Apparatus; b. Exploded view in perspective of the chiller with its main components

Figure 5 shows the results of the energy and exergy balances for the two-bed chiller with simultaneous adsorption during the phase changes. The results of the experimental tests using the silica gel / water pair from the Matlab® script coupled to the REFPROP were met with a SCP and a COP of, respectively, de 81,4 $W \cdot kg^{-1}$ and 0,52 with an exergetic efficiency of 8,2 %, for the best working conditions, represented by the triplet 72/30/15 ℃ and a cycle time of 35 min.

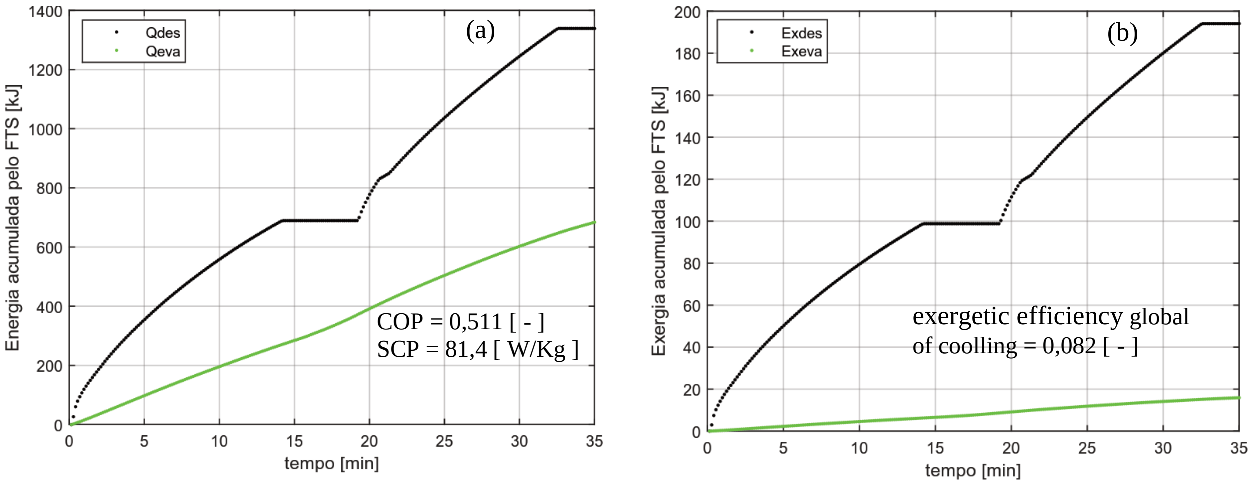

Figure 5. Graphs of (a) energy and (b) exergy performance. Adsorption cycle with a 35 min duration.

Table 1 shows the exergy destruction (ExD) data as well as the specific exergy destruction (ExDS) and the participation percentage of each component in the performance of the system, with regard to a cycle with simultaneous adsorption with 35 min of duration, obtained from the experimental data, evidencing that the adsorptive reactor is the component that contributes with the highest percentage of exergy destruction, followed by the condenser and then the evaporator.

Table 1. Cumulated destroyed exergy in each component of the two-bed chiller for a cycle of 35 min.

Componentes →	**Evaporador**	**Reator**	**Condensador**	**Total**
ExD [W]	25.25	105,21	88,77	219,23
ExDS [W/kg de adsorvente]	2,9	12,2	10,3	25,4
ExD [%]	11,42	48,03	40,55	100

4. CONCLUSION

In this paper, we experimentally investigated the concepts of energy and exergy for an adsorption cooling system with two reactors applied to air conditioning. The two-bed chiller was developed with a finned tube heat exchanger filled with solids of silica gel with regeneration made with a low quality source, around 75oC, for regeneration of the adsorbers. Experimentally an SCP of 81,4 $W \cdot kg^{-1}$ and 52 % efficiency with an exergetic efficiency of 8.2 % was achieved for the best working conditions, represented by the triplet 72/30/15 ℃ and a cycle time of 35 min. An analysis of the exergies destroyed in each component of the two-bed *chiller* presents the reactor as the main item of irreversibility of the system, which can be improved punctually and, consequently, with lower cost.

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