SOFTWARE DEVELOPMENT TO PREDICT THE FLOW WATER IN BEDS ADSORPTIVE

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Abstract. The high energy consumption of air conditioning has led to the development of alternative cooling systems. The air conditioning by adsorption bed containing an adsorptive effect capable of producing a refrigerator through evaporative cooling is one alternative to replace the air conditioning vapor compression in specific applications. The possibility to use solar energy to supply the energy needed for regeneration of adsorbents makes this alternative very feasible in tropical countries such as Brazil. However, the hot water cycle should be well sized to avoid unnecessary energy waste and mixtures in the heat storage tank. To this end, it is important to evaluate the return of hot water from the storage tank adsorbents. This paper aims to present the development of a computer program called SimAds, able to simulate the flow of water within a adsorptive bed and indicate the time required for regeneration of the same and the profile of the hot water that leaves the bed to return the thermal storage tank. The SimAds generated the hot water temperature data to study the air conditioning central heat storage adsorptive SLE - UFPB, still in the installation phase. The software results were compared with experimental results in flow bed adsorptive raised by SAHA et al. 2013 and showed average errors of 1.37 K at exit temperature, and 12.4% in the time for heating the bed.

Keywords: air conditioning, refrigeration by adsorption, numerical simulation, adsorptive bed regeneration.

1. INTRODUCTION

The vapor compression chillers, more used, in addition to contributing to the increase in electricity consumption and therefore to the energy bill enhancement, presents some issues regarding the environmental impacts such as global warming, depletion of the ozone layer and air pollution also caused by refrigerants. In Brazil, the use of solar energy as a power source for air conditioners is a prominent idea since the country has an extensive area of land and a large availability of this type of energy (TIBA, 2000). Together with the development of systems that disposes a vapor compressor in refrigerators, as in the case of the air conditioner by adsorption studied in this work contributes significantly to solving the problems described above.

The current state of art of adsorption cooling systems using solar energy with a comprehensive literature review was presented by FERNANDES et al. (2014), in a paper which concluded that simple cycles of adsorption can be attractive alternatives not only to meet the cooling needs, but also to meet demands for energy conservation and environmental protection. SUMATHY et al. (2002) also presented a detailed analysis of the latest efforts in the field of solar cooling systems to improve the performance of adsorption subsystems powered by solar energy. Thereby concluding that for the proper functioning of these systems and the choice of solar collector design and the arrangement of the subsystems, a careful selection of the adsorbent - adsorbate pair is essential.

An adsorption refrigeration equipment is being built in LES - UFPB ever since the beginning of the project designed by RIFFLE (2008). This equipment has enabled methanol as a carbon adsorptive pair, cooling capacity of 20 kW and preferably utilizes solar power as an energy source. In addition to the main cycle, composed primarily of evaporator adsorbers, condensers and expansion valve. The air conditioning system that was studied has a cold water loop composed of a pump, a reservoir of cooling tower and a hot water cycle formed by solar collectors, additional gas heater , pump and hot water tank . These two cycles alternately act inside the adsorptive bed to provide better conditions of respectively adsorption and sorption.

The air conditioning system considered is shown in figure 1. It consists of solar collectors, a hot water storage tank, an activated carbon methanol adsorption (water-cooling unit), a gas heater, a cold water tank and an air–water heat exchanger (fan-coil). The adsorption system is composed by four compact heat exchangers. The others air conditioners devices are two air condensers, one evaporator, and accessories such as valves and circulation pumps.
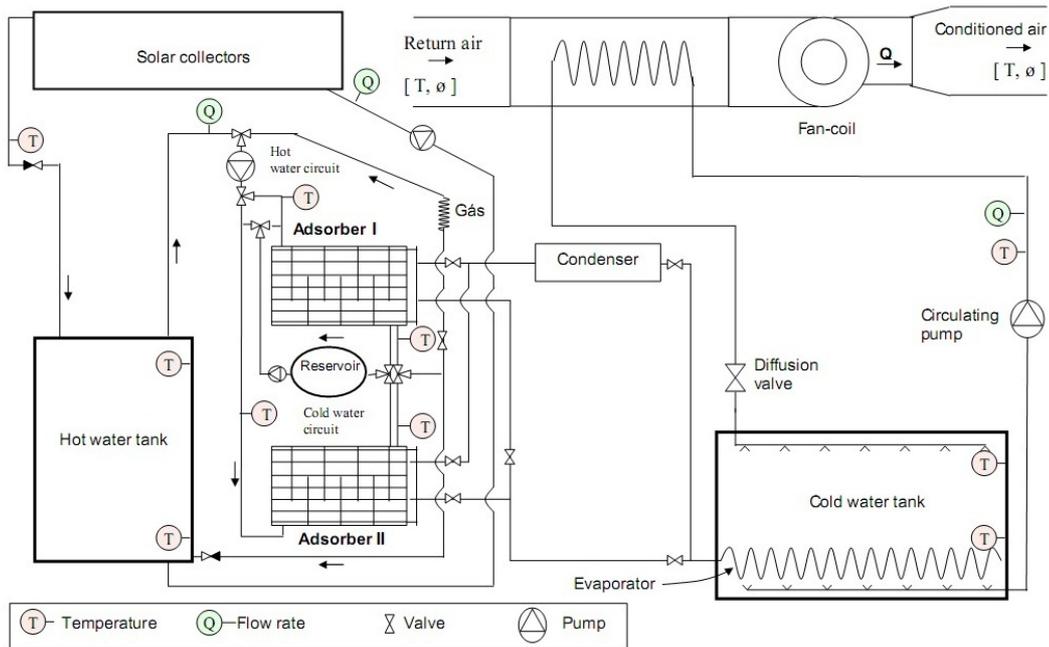
Figure 1. Schematic operation of the solar energy/natural gas adsorption air conditioning system [LEITE et al. (2011)].

This air conditioning system is based on an activated carbon - methanol adsorption cycle with heat recovery, where the steps of regeneration and production of refrigeration effect occur simultaneously, i.e., the absorbers (I and II, showed in fig. 1) working alternately are responsible for cooling the water in the thermal storage tank. Methanol flows through a compact heat exchanger evaporator, in order to cool the water in the cold-water tank. The conditioned air is obtained by changing heat between the stored chilled water and the airflow through a fan-coil. Then, it is distributed to the rooms by a network of tubes. The cold water circuit, whose function is to provide cooling while the adsorbers are in the adsorbing phase, is composed of a storage tank for cooled water and a small centrifugal pump. In the other way, the hot water circuit uses a solar collectors field as the thermal source for the regeneration process.

The adsorption porous bed is placed in compact heat exchangers, and their physical characteristics were obtained from numerical simulations [RIFFLE (2008), DOMINGOS et al. (2010)]. They were constructed in four modules with a finned-tube heat exchanger geometry and they should operate in a parallel-series arrangement as shown in figure 1.

The condenser and the evaporator are both constructed as a finned-tube heat exchanger geometry. and their related equations were widely described and experimentally validated on a previous RIFFLE et al. (2009). From the simulation data, the evaporator must operate continuously (i.e., during 24 hours a day) to ensure the storage of chilled water required by the air-water heat exchanger (fan-coil), in order to provide the desired temperature for the rooms` inlet air. A compact plate heat exchanger evaporator was set to provide the designed operating conditions and to ensure that the outlet methanol is completely superheated. The regeneration system comprises a field of flat solar collectors with a high efficient transparent cover, coupled to a thermal storage tank. The water previously heated by the solar energy will get the desired temperature of 100°c with the help of a small "pass type" gas heater which is located after the heat storage tank.

The collectors' field was installed in a parallel-series arrangement, in two symmetrical blocks, each one consisting of 38 units of adapted commercial flat collectors of 1.58 m^2 each – totaling 120 m^2 of solar catching area, with an inclination of 9° facing to the South (Fig. 2a). It is located in Joao Pessoa (7°8′S, 34°50′WG), whose climate is typically hot and humid. The pre heated water , coming from the collector is stored in the make up tank shown in Figure 2b.
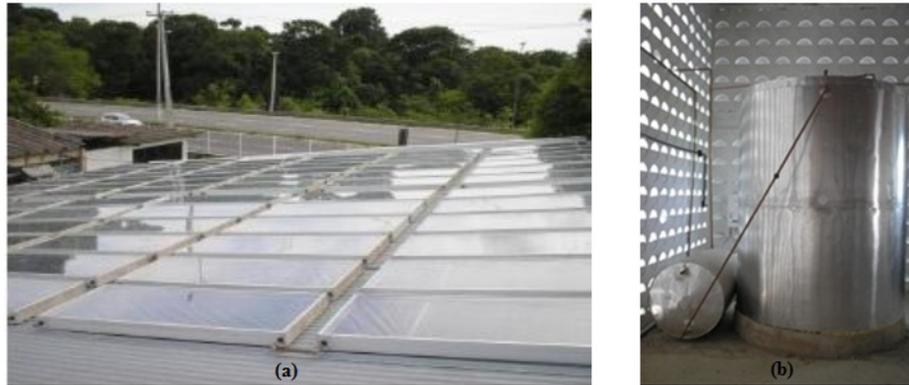
Figure 2. (a) Field of flat plate collectors installed on the roof of the LES/UFPB laboratory. (b) Main storage and feed tanks.

Fig. 3 illustrates the path of fluid (water) in the hot water cycle and Fig. 4 shows the geometric and constructive characteristics of the adsorbent of the finned shell-and-tube type which was designed from LEITE and ADOLPH (2013) and was used in this project. The empty space between the copper fins are filled by activated carbon, while the water flow which heats the bed during the regeneration phase runs through the copper tube (diameter of 1/2 inch) which is shown in the same figure . The adsorber has a total length of 95.786 m, 7 beams with mass water flow 0.1 kg.s -1 and surface area of 4,37m² . These and other features of the adsorber and flow of water inside can be found in the work ADOLFO (2015).

The purpose of this article is to describe the SimAds software, created by the need of knowledge of the properties of thermal water flow within the adsorbents belonging to the refrigeration equipment for existing adsorption in LES-UFPB . The software SimAds interest is to study the heating profile of the adsorptive bed and the temperature of the fluid in the outlet pipe even during the regeneration phase . It is known that this piping temperature profile is directly compared with the performance of thermal stratification of the hot water storage tank and, consequently, the efficiency of the system.
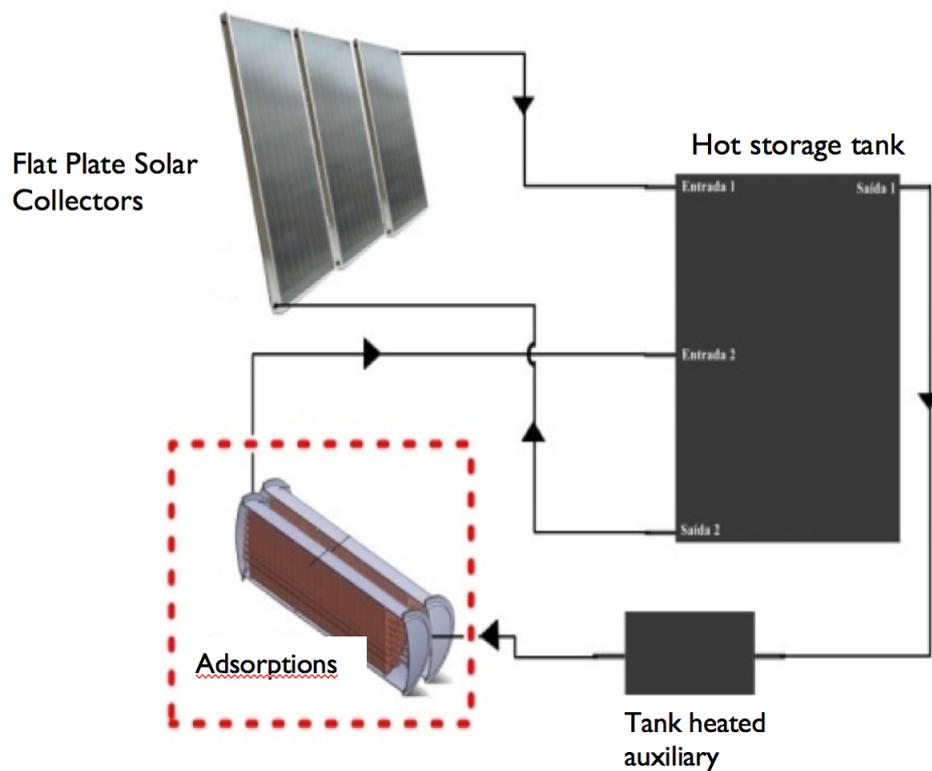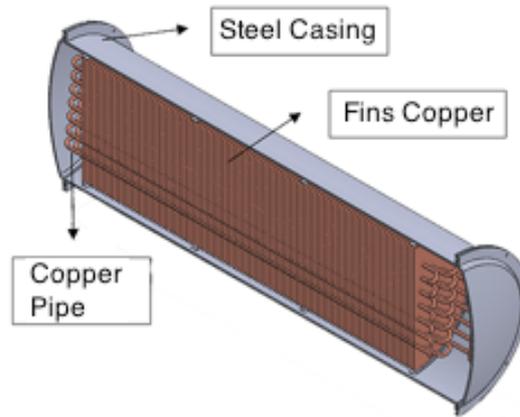

Figure 3. Hot water cycle

Figure 4. Longitudinal section of the adsorptive bed .

2. METODOLOGIA

The SimAds software was created in the virtual environment of commercial development CodeBlocks using the C ++ programming language that allows object-oriented programming and the use of environment files when the application is run. Programming was done by means of classes, which are data structures that contain blocks methods that manipulate the data. The use of this programming framework allows you to leave the most intelligible and robust code, both for the user and for any maintenance and evolution of the algorithm by the developer. The classes are designed to total three: Simulator, Adsorber and Interpolation. The analysis of the flow of water inside the adsorber involves a temperature gradient along the bed length. In order to ensure better compliance of the results, rather than on a comprehensive analysis of the entire system, we chose to study the pipe into small pieces of Ax length [m] and small time steps Dt [s] defined but the user.

It is considered that for a given time step, the bed temperature is the same from the beginning to end of the length of tubing that runs inside it. In order to avoid predictions about the desorption kinetics of the system, the mass transfer was disregarded adsorber during the regeneration process for the simulation of the flow within it, the bed being maintained at the same mass during the heating process. For this reason also, the heat exchange that occurs during the regeneration of the adsorber is neglected. The water flow equally distributed is considered for each pipe bundle and that during the initial moments of disposal regions in which the hot water flow has not reached still have water at the same temperature as the adsorber and, therefore, not contribute to its heating. The simplifying assumptions are important to facilitate the approach was made entirely based on the energy balance of the adsorptive bed in a transient flow.

$$h_l = \frac{Nu \cdot c}{\phi} \cdot Per \tag{1}$$

$$E_{exchanged} = h_l \cdot (T_{water} - T_{adsorber}) \cdot \Delta x \cdot \Delta t \tag{2}$$

$$T_{water} = \frac{E_{Previous\ energy} - E_{exchanged}}{C_p} \tag{3}$$

The equation used by the program begins with the calculation of the average speed of the water inside the pipe, obtained from the mass flow rate specified by the user, making it possible to calculate the Reynolds number flow. In possession of this data, the program returns the screen Reynolds dimensionless found and asks what method you prefer to use to calculate the Nusselt number with equations based on BERGMAN et al. (2011) that depends on the range of Reynolds estimated by the software. Then, the code calculates the heat transfer coefficient by convection unit length per h_l *[Wm-1.K-1]* by Eq. (1) and thereafter is the energy exchanged between a pipe length Δx and the adsorptive bed at a time step (Δt) by Eq. (2) where T_{water} is the temperature of the water inside the pipe *[K]* and $T_{adsorber}$ is the temperature of the adsorber *[K]*. After this, the water temperature is calculated for the next piece of Δx length by means of Eq. (3). Eqs. (2) and (3) do not have the mass flow of water as a variable, but the magnitude is characterized by the coefficient h_l. The reason enters again in the calculation when a new step is added, the moment in which the volume of the water is renewed inside the tabulation.

Where *Nu* is the dimensionless Nusselt, *c* is the thermal conductivity of water *[Wm-1.K-1]*, ϕ is the pipe diameter *[m]*, *Per* is the perimeter *[m]* and C_p is the specific heat of water *[J. kg-1.K-1]*. This is done for each space length until they reach the total length of pipe within the adsorptive bed. The water temperature found at the end of this cycle of the program is recorded as the temperature of the bed water outlet for that particular step of time. It is also interesting to note that during the beginning of the heating process, there are cold water pipes within the adsorbent. Therefore, there is a time period in which the flow of hot water makes its way, but does not reach the end. For these times, the SimAds

considers that the water outlet temperature is equal to the adsorber temperature, ire. Includes the water present inside the bed in the total thermal inertia and discards the convective heat transfer in the axial direction of the pipe.

Before leaving for the next time step, the code also calculates the energy loss through the walls of the adsorptive bed within that time step by Eq . (4) where p is the thermal resistance of power loss to the environment [KW -1] to be selected by the user and It depends on constructional properties of the bed. After a time step , the software can find the energy of the adsorber in the next step of time (greater than the previous) by Eq . (5)

$$E_{lost} = \frac{T_{adsorber} - T_{environment}}{R_p} \tag{4}$$

$$E_{current\ adsorber} = E_{previous\ adsorber} + \sum_{i=0}^{n} E_{exanged} - E_{lost} \tag{5}$$

Where the sum operation indicated in the second term of the equation of the right side represents the sum of all calculated for each Retrograde Δx space length before. Thus, it is possible to find the temperature of the adsorptive bed to the next step time by using Eq . (6) where the sum of the divider is the thermal inertia of the entire constituent mass of the bed, with all the masses of the constituent materials the adsorber.

$$T_{adsorber} = \frac{E_{current\ adsorber}}{\sum_{i=materia}^{n} m_i \cdot C_i} \tag{6}$$

This temperature is also recorded by the program each time step and is shown as a solution. An important feature of SimAds is that whenever a property of water is demanded, this is sought in a table of properties depending on the working temperature through data interpolation. The table used in this study, had their data collected according to Steadicam software, available online, using data according to the International Association for the Properties of Water and Steam (APIA) Industrial Formulation 1997 recommended by SAME. The program routine can be exemplified by the flowchart shown in Fig . 5. In this it is possible to observe how the iterative process of changing the time step.
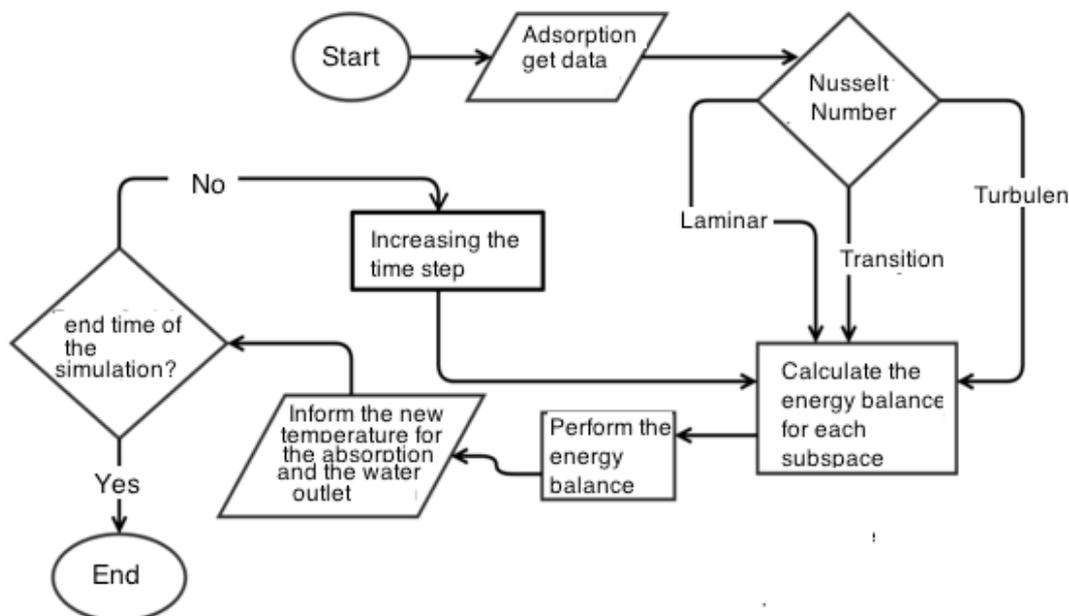

Figure 5. Flowchart of routine SimAds program.

3. RESULTS

To evaluate the error of the results due to the area and the time step discretizations, we conducted a study with different discretizations for Δx and Δt . By working in a case without power loss through the walls of the adsorptive bed and Ax values of 5 cm, 2 cm, 1 cm, 5 mm, 2 mm and 1 mm there was no significant difference between the results evaluated . In all cases the time for heating the adsorber to 99 % of the design temperature is up to 99 % of the outlet temperature were respectively 320 s and 195s. Due to the high speed software in any case chosen to work with a final Ax 5 mm.

Likewise, we worked up in a simulation using the steps of time: 5s, 2s, 1s, 0.5s and 0.2s . The results, this case showed a little divergence, with times for heating the adsorbent ranging between 318 s and 321.6s . The relative error between the measured time to time 0.5s and 0.2s step, however, was only 0.19%. In the study the average temperature of the adsorber outlet , the error between the results obtained with the two smaller steps and less time was 0.07%. For this reason , the time step adopted definitively was 0.5s.

The energy loss through the walls was considered the main simulation , a factor that proved to be very relevant in the bed heating time. The heating time of the adsorber LES - UFPB cooling system stood at 391.5s and the evolution of the adsorber , and the water outlet along the flow time of temperature can be seen in Fig . 3 (a). SAHA et al . (2000) showed an article in the behavior of the temperatures of cold water and hot water circuits before and after passing the adsorption beds as well as the inlet and outlet temperatures of the cooled water through the system evaporator . Fig. 4 shows the results obtained by SAHA et al. 2013 Exit temperature of the hot water behavior similar to that proposed software.

In Fig. 6 is observed that there is a time until the flow time 120s in which the two temperatures analyzed are identical. This occurs because the time that the flow of hot water takes to traverse the entire length of the pipe. It is also observed that at the beginning of the flow, the fact that the hot water is entering the bed, set up a heating that accelerates over time, soon becoming a decelerated heating . This behavior is also observed in experimental studies with adsorptive beds.

The case of regeneration of adsorber SAHA et al . It was played in SimAds software in order to validate the methodology used in the program. Found a mean relative error of 0.43 %, with an average deviation of 1.37 K between the two curves . The graph of Fig. 5 shows the comparison between the hot water outlet of the adsorber results obtained by SAHA et al . experimentally obtained by numerical routine SimAds . The heating time of the adsorbent was found by the software of 472 s, whereas the experimental data found by the authors indicate that time of 420 s.

In considering the outlet temperature of the adsorbers to enter the hot water storage tank in the air conditioning design by adsorption, one has to observe that the behavior shown in Fig .7 is repeated, as in Fig. 8. This is because when an adsorber regeneration ends , always one second adsorber enters its place so that the refrigerator effect is not interrupted. Fig. 9 shows what happens to the hot water outlet of the adsorbers over time considering the exchange adsorbents , results that serve as boundary condition for the input 2 of the storage tank shown in Fig. 1.
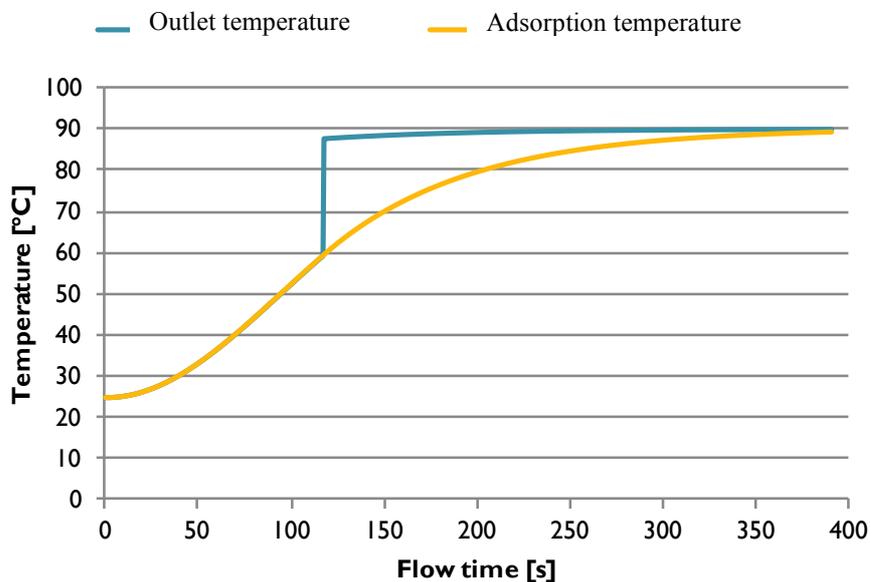

Figure 6 - Behavior temperature in the bed temperature and the hot water outlet (SimAds)
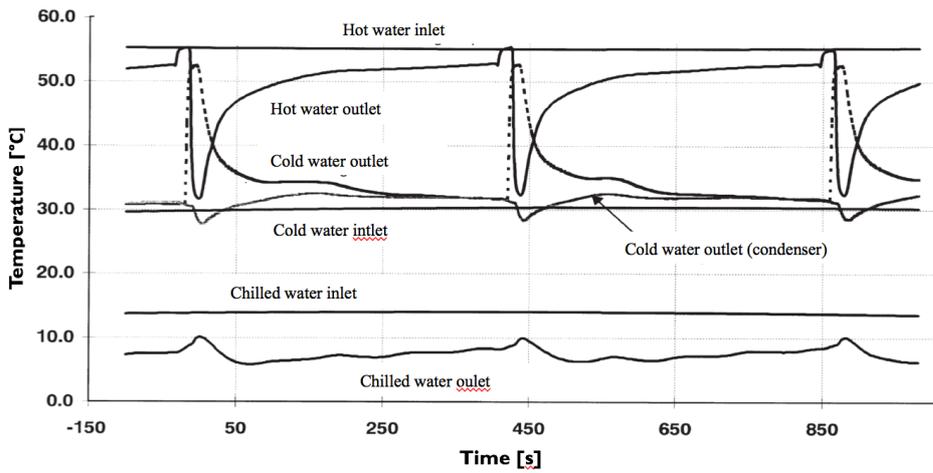
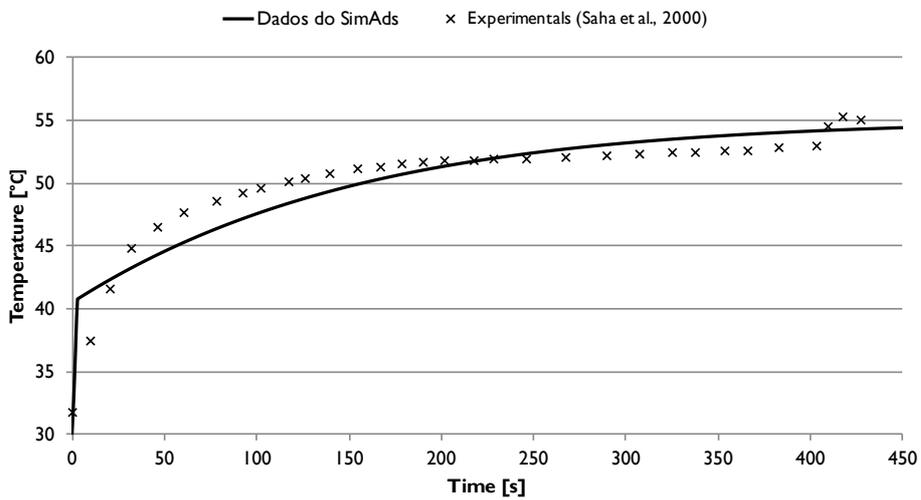*Figure 7 - Temperature profiles to hot water cycles and cold refrigerated (SAHA et al. 2013).*

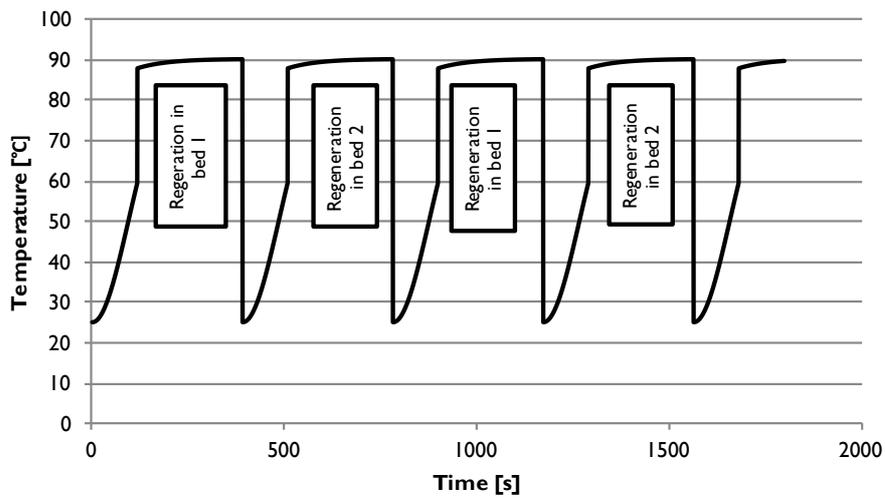Figure 8. Experimental data (SAHA et al., 2013) x data of numerical simulation (SimAds).

Figure 9. Leaving water temperature of the adsorbers considering the exchange adsorption beds.

4. CONCLUSIONS

Any adsorber heating time and the temperature profile of the hot water outlet of adsorptive bed regeneration obtained by SimAds software proved consistent with the experimental results found by SAHA et al. 2013 This indicates that the methodology used in numerical routine SimAds can play efficiently heated under adsorber behavior, even with the simplifying assumptions in section 2. The use of SimAds can be very useful for the study of energy efficiency of air conditioning equipment, and can even estimate the desorption time on a similar project adsorptive bed of hull – pipe finned type. The inclusion of a mathematical -physical model to simulate the mass transfer during the desorption process can significantly contribute to increasing the accuracy of the results.

5. ACKNOWLEDGEMENTS

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