AIR CONDITIONING SYSTEM OF 20KW BASED ON SOLAR-GAS ADSORPTION

Celina M. C. Ribeiro[1], Daniel Sarmento[1], Francisco A. Belo[1], Douglas B. Riffel[2], Belkacem Zeghmati[3], Antonio P. F. Leite[1]

[1] Solar Energy Laboratory, Federal University of Paraíba, João Pessoa-PB, Brazil

[2] Mechanical Engineering Department, Federal University of Sergipe, Aracajú-SE, Brazil

[3] Laboratoire des Mathématiques Et Physique des Systèmes, Université de Perpignan Via Domitia, Perpignan, France

1. Introduction

This paper presents the ideal operation conditions of a 20 kW central air conditioning prototype based on an adsorption with activated carbon-methanol pair and a hybrid regeneration (solar/gas). The prototype is in development at the Solar Energy Laboratory (LES) of the Federal University of Paraíba (UFPB), in Joao Pessoa, Northeastern Brazil.

The regeneration heat is provided by a field of high efficiency flat plate solar collectors, with a total captation area of 120 m^2. The air conditioning was designed for operating with a maximum of solar energy with the complementary heat being supplied by a natural gas heater. The design data were obtained for a typical summer day in Joao Pessoa, at a latitude of 7°S, from a meteorological database.

The results were obtained from a computer simulation program (ADSOL), which was carried out using the Simulink interface, with functions created in Matlab® (Domingos et al., 2010). It simulates the overall operation of the air conditioning unit, by coupling the solar collectors field with the storage tank and the adsorbers, depending on the conditions of heat recovery between the adsorbers. It also analyzes the different operation parameters in order to obtain those for producing the maximum performance with the minimum gas consumption.

The variables considered in the simulations are: the heat transferred to the adsorbers, the cycle duration of sorption/desorption for different scenarios of heat recovery between the adsorbers, flow and temperature of the water previously heated by the solar collectors field and the gas heater. The influence of the operating parameters on the coefficient of performance (COP) and on the specific cooling power (SCP) is also evaluated.

2. Abstract

This paper presents constructive aspects and preliminary experimental results of an adsorptive chiller as part of a 20 kW central air conditioning unit for providing thermal comfort in a set of rooms that comprises an area of 110 m^2. Some simulation results of the air conditioner regeneration system are also presented. The cooling system is basically made up of a cold-water storage tank – supplied by an activated carbon-methanol chiller, and a hot-water storage tank – fed by a field of high efficient solar collectors with complementary heat by natural gas. The adsorber – a compact heat exchanger containing the activated carbon – was conceived and constructed in four modules, in order to allow heat and mass recovery. Other components are the same existing on conventional central air conditioners, as a condenser, an evaporator and a cooling tower. Constructive details of the collector's field, the adsorbers and the regenerating storage component are shown. The solar system is a 120 m^2 collection area field composed by 76 units of a flat plate collector covered with a high efficient transparent insulation. Results obtained previously from a multi-objective optimization based on a statistic modeling shown that – for a specific cooling power of 120 W kg^{-1} of adsorbent – an expected chiller's COP of 0.6. With this COP value, and considering the mean value of the total daily irradiation in João Pessoa (7º8'S, 34º50'WG), the expected solar energy cover fraction of 75%, for a typical summer day. This scenario was predicted for the following operation temperatures: 30°C for the condenser, 7°C for the evaporator and 105°C at the start of the regeneration process. For an acclimatization period of 8 hours (9 to 17 h), the main dimensioning parameters were: 504 kg of activated carbon, 180 liters of methanol, 7,000 liters of hot water, 10,300 liters of chilled water with its temperature varying in the fan-coil from 1°C to 14°C. The ideal size of the

storage hot tank was obtained by a previous simulations, which also evaluate the ideal water flow rate in the set of collectors that provides the lower gas consumption while the system reach a regeneration temperature.

In the present paper, the water flow in the adsorbers was examined for different flow rates (0.0001 $m^3 s^{-1}$, 0.0002 $m^3 s^{-1}$, 0.0003 $m^3 s^{-1}$, 0.0004 $m^3 s^{-1}$ and 0.0005 $m^3 s^{-1}$). The results have shown that 0.0001 $m^3 s^{-1}$ is the value which provides the lower gas consumption, for a solar collectors flow rate of 0.0004 $m^3 s^{-1}$. It is also presented in this paper the influence of the parameters of the system on the coefficient of performance (COP) and on the specific cooling power (SCP).

3. Features of the central air conditioning unit

3.1. Description of the system

The central air conditioning unit consists basically of 3 components: a cold-water storage tank – fed by an activated carbon-methanol chiller, a hot-water storage tank – fed by a field of high efficient solar collectors with complementary heat by natural gas, and an air-water heat exchanger (fan-coil).

3.1.1 Cold-water storage tank

The cold water of the cold-water storage tank is supplied by an activated carbon-methanol chiller, comprised by four adsorbers, the condenser, the evaporator and the cooling tower. The adsorbers – a compact solid/liquid heat exchangers – are the main part of the chiller. They was conceived and constructed in four modules, in order to allow heat and mass recoveries.

The adsorption chiller operation was simulated using a model developed by Riffel (2008). It was investigated statistically the results of the dynamic model of the adsorber in order to obtain the optimum project parameters, taking into account the best operating points and the influence of seven variables (temperature and mass flow of hot water, cycle length, number of tubes, number of fins, fin thickness and material of manufacture) (Riffel et al., 2010a). The results showed that all variables are statistically significant and interdependent. As a main result, we observed that the COP is highly dependent on the number of fins, the material and the cycle length. The inner surface of the adsorber, exchanges heat with water from a hot or cold source, depending on the phase of the cycle. The adsorbent occupies the space delimited by the external wall of the tube and the corrugated fins. The adsorbent bed operates under vacuum for getting the required thermodynamic properties of the working fluid (the methanol). The micropores of the adsorbent medium has a diameter smaller than 2 nm. In the case of specific cooling power (SCP), the most important variables were the number of fins, the number of tubes and the hot water temperature.

The condenser and the evaporator are a finned-tube heat exchanger widely described and experimentally validated on a previous paper (Riffel et al., 2010b). From the simulation data, the evaporator must operate continuously (i.e., during the 24 hours a day) to ensure the storage of chilled water required by the heat exchanger air-water (fan-coil) and thus provide the design temperature for the inlet air of the rooms (= 14 °C). For the evaporator we selected a compact plate heat exchanger, manufactured by CIAT (French). The equipment will be adapted for the required operating conditions, to ensure that the outlet methanol is completely superheated (Riffel et al., 2009).

3.1.2 Hot-water storage tank

The cylindrical tank needed for the hot water storage was built in steel, with 2.074m of diameter, 2.50m of height and insulated with 50mm thick polyurethane foam. It is fed by a field of high efficient solar collectors with complementar heat supplied by the combustion of natural gas. The water previously heated by the solar energy will get the process temperature with the help of the small gas heater, model GWH 300DE-GN – BOSH.

The field of solar collectors was installed in a parallel-series arrangement, in two symmetrical blocks, each consisting of 38 units of a commercial flat collectors of 1.58 m^2each, covering a total catchment area of 120 m^2, installed on the roof with an inclination of the 9° facing to the South (Figure 1), which corresponds to the average value for the six hottest months in João Pessoa (7°8′S, 34°50′WG), whose climate is typically hot and humid (Domingos et al., 2010).

Fig. 1: Field of high efficient solar collectors installed in the LES/UFPB.

The absorbing surface of the collectors is painted in nonselective matte black, and there is a Teflon film placed between the absorbing surface and the glass cover plate, specially treated to resist UV rays (Figure 2), which constitutes a high efficient transparent insulation material (TIM). The distance above and below the Teflon film is about of 25mm, which is considered optimal to minimize radiation and convection heat losses (Leite et al., 2003, 2005).

Fig. 2: Scheme of TIM cover.

The small natural gas heater, model GWH 300DE-GN – BOSH, will heat the water from the hot water tank until the temperature of 105°C to ensure the regeneration. The simulation program calculates the total amount of natural gas need to be consumed in one day.

3.2 Heat transfer equations

For the collectors and the chiller, empirical correlations and simple methods of energy balance were used. For the storage tank, the function was based on the finite volume method. The equations related to the condenser and evaporator were widely described and experimentally validated on a previous paper (Riffel et al., 2010b).

3.2.1 Solar collectors

It was used the quadratic efficiency collector (equation 1) which estimates the average efficiency for a field of collectors at a given time (Duffie and Beckman, 1980), and a simple energy balance for each collector (equation 2). The constants a_0, a_1 and a_2 depend on the characteristics of the collector, and also takes into account the arrangement of the collectors (parellel-series) that was disposed in two sets of 38 collectors each one.

$$\eta = a_0 - a_1 \frac{T - T_a}{Rad} - a_2 \frac{(T - T_a)^2}{Rad} \quad \text{(eq. 1)}$$

$$T_i = T_{i-1} + \frac{\eta \ A \, Rad}{\dot{V}_{col} \, c \, \rho} \quad \text{(eq. 2)}$$

Where: T is the temperature of the solar collector, T_a is the ambient temperature; Rad is the solar radiation at a given time; T_i is the temperature of the i-th collector in serie, A is the transparent area, $\dot{V}_{col}$ is the water flow in each collector in parallel, c is the specific heat of the water and ρ is the density of the water (properties taken in the inlet temperature).

3.2.2. Adsorption chiller

The operation of this system is described by a statistical model developed by Riffel (2008), considering various parameters of the air conditioning system. The equation 3 represents the energy balance for the water that flows through the adsorbent. Losses in the pipeline and the delayed response in thermal heat exchanger (adsorber) were not considered.

$$T_{out} = T_{in} - \frac{SCP}{COP} \cdot \frac{m_{ads}}{V_{ad}\, c\, \rho} \qquad \text{(eq. 3)}$$

Where, T_{out} and T_{in} are, respectively, the water temperatures at the exit and entry of the adsorbers, m_{ads} is the total mass of adsorbent (activated carbon), and V_{ad} is the water flow in the adsorber.

3.2.3 Hot water tank

The geometry of the hot water storage tank is cylindrical, which h is connected at the bottom and the top with the solar collectors and the adsorbers. For calculating the heat exchanges in the tank the finite volume method was used and it was considered a stratified tank with one-dimensional heat transfer. The stratification occurs in layers of increasing density and decreasing temperature. This method presents a numerical solution that enables problem solving under any initial conditions and it consists in dividing the tank into a finite number of longitudinal nodes of same temperature and volume.

The solution of the equations is performed by implicit formulation and the method of matrix inversion. The model of the hot water tank was developed by Riffel et al. (2007).

3.2.4 Natural gas heater

For the natural gas, the simulation program calculates the total amount of natural gas need to be consumed in one day.

$$Q_{gas} = v_{gas}\, PC \qquad \text{(eq. 4)}$$

$$Q_{gas} = \frac{Q_{water}}{ef_{gas}} \qquad \text{(eq. 5)}$$

$$Q_{water} = c\ \rho\ v_{\tan k}\ (T_{in} - T_{\tan k}) \qquad \text{(eq. 6)}$$

Where Q_{gas} is the heat supplied by the gas heater; PC = $38{,}540e^{+6}$ (J m^{-3}); v_{gas} is the volumetric flows of the gas; ef_{gas} is the efficiency of the gas heater (= 0.80); T_{in} is the hot water temperature at the exit of the gas heater (at the entrance of the adsorber); $v_{\tan k}$ is the volumetric flow of the adsorbers.

4. Results and analysis

4.1. Results

Many simulations have been carried out using the ADSOL code to determine the optimal operating parameters of the system and to analyze their influence on the COP (coefficient of performance) and on the SCP (specific cooling power).

An important decision taken based on the simulation was the definition of the volume of hot water tank to obtain a minimum consumption of gas needed to heat the water of regeneration. It was searched in the previous simulations, with some considerations showed in the Table 1. The results are showed in the Figure 3.

Tab. 1: Parameters of simulation.

Parameters of simulation	
Description	**Value**
chilled water temperature (Te)	7°C
cold water temperature (Tc)	5°C above the ambient temperature
water regeneration temperature (Tr)	105 °C
mass of the adsorbent (activated carbon) for each adsorber	116 kg
adsorber water flow (v_ads)	0.0001 $m^3 s^{-1}$
Solar collectors water flow (v_col)	0.0005 $m^3 s^{-1}$
typical summer day	January 2010

Based on the consumption of the natural gas for the volumes of hot water tank between 1m^3 and 9 m^3, during 24 hours, we can observe that between 5m^3 and 7m^3, there is the minimum flow limit, thus defining the adoption of the tank of a 7m^3 of volume (Domingos et al., 2010).

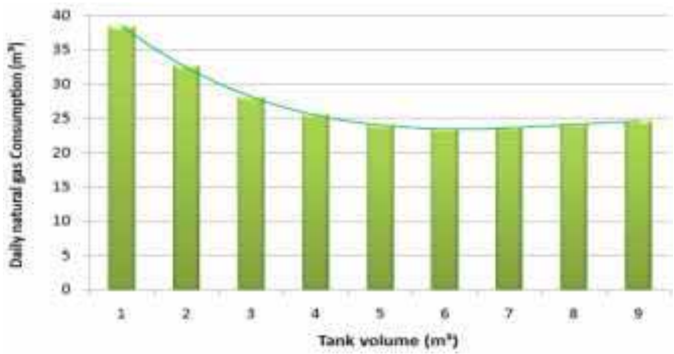

Fig. 3: Comparison of the daily natural gas consumption to the hot water tank volume between 1m^3 and 9m^3.

Taking the hot water tank volume equal to 7m^3 and the same parameters used for the analysis, the water flow rate in each set of collectors in parallel arrangement was examined for different volumetric flows (v_col = 0.0001 $m^3 s^{-1}$, 0.0002 $m^3 s^{-1}$, 0.0003 $m^3 s^{-1}$, 0.0004 $m^3 s^{-1}$ and 0.0005 $m^3 s^{-1}$) to verify which of them provides the lower gas consumption.

The Figure 4 shows the daily consumption of natural gas, for the water collector flow rate between 0.0001 $m^3 s^{-1}$ and 0.0005 $m^3 \cdot s^{-1}$, necessary for heating the adsorber (Leite, 2011).

Considering these values, the water flow in the adsorber was examined for different volumetric flows (v_ads = 0.0001 $m^3 s^{-1}$, 0.0002 $m^3 s^{-1}$, 0.0003 $m^3 s^{-1}$, 0.0004 $m^3 s^{-1}$ and 0.0005 $m^3 s^{-1}$), with the hot water tank volume equal to 7m^3 and the water collector flow equal to 0.0004 $m^3 s^{-1}$. The results are showed in the Figure 5 (Ribeiro, 2011).

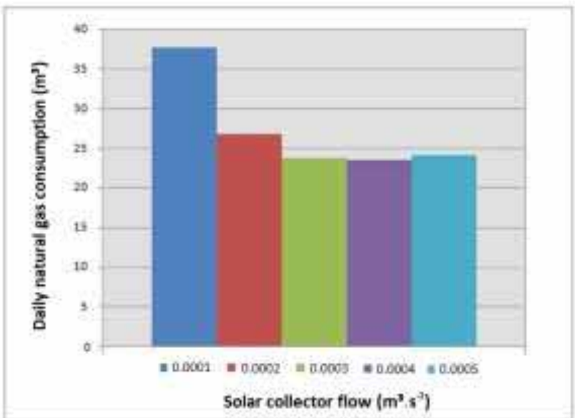

Fig. 4: Daily consumption of natural gas for different flow rates in the set of collectors.

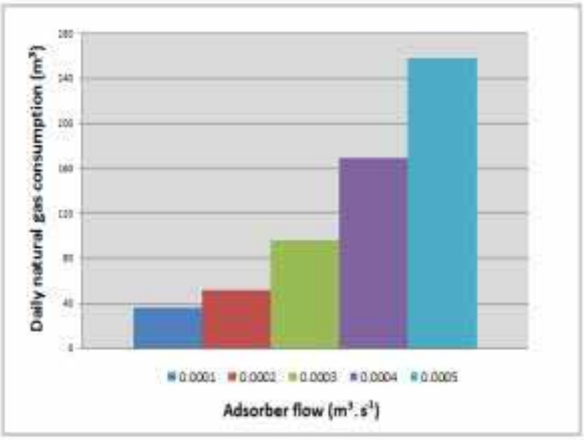

Fig. 5: Daily consumption of natural gas for different flow rates in the adsorber.

It is also verified the influence of the system parameters on the coefficient of performance (COP) and on the specific cooling power (SCP) for several values of v_col and several values v_ads, with Tc = tamb+5°C, Tr = 105 °C and Te = 7 °C (Table 2).

Tab.2: COP and SCP for different water flow rates in the adsorber.

v_ads	**v_col** ($m^3 s^{-1}$)	**COP**	**SCP**($W kg^{-1}$)
0.0001 $m^3 s^{-1}$	0.0001	0.46	86
	0.0002	0.46	86
	0.0003	0.46	86
	0.0004	0.46	86
	0.0005	0.46	86
0.0002 $m^3 s^{-1}$	0.0001	0.48	122
	0.0002	0.48	122
	0.0003	0.48	122
	0.0004	0.48	122
	0.0005	0.48	122
0.0003 $m^3 s^{-1}$	0.0001	0.51	206
	0.0002	0.51	206
	0.0003	0.51	206
	0.0004	0.51	206
	0.0005	0.51	206
0.0004 $m^3 s^{-1}$	0,0001	0.54	337
	0.0002	0.54	337
	0.0003	0.54	337
	0.0004	0.54	337
	0.0005	0.54	337
0.0005 $m^3 s^{-1}$	0.0001	0.57	514
	0.0002	0.57	514
	0.0003	0.57	514
	0.0004	0.57	514
	0.0005	0.57	514

Another important verification was for the influence of the system parameters on the COP and on the SCP for the fixed values of the volumetric flows of the adsorber and the solar collector, for different values of condensation, regeneration and evaporation temperatures, to determine the optimal parameters for system operation. The results are shown in Table 3 (Ribeiro, 2011).

Tab.3: COP and SCP for $v_{ads} = 0.0005$ m^3 s^{-1} and $v_{col} = 0.0004$ m^3 s^{-1}.

T_{cond} (°C)	T_{reg} (°C)	T_{ev} (°C)	COP	SCP (W kg^{-1})
T_{amb}+5	105	7	0.57	515
		10	0.46	505
		15	0.28	484
T_{amb}+3	105	7	0.56	516
30	***100***	***7***	***1.93***	***928***
		10	1.82	872
	105	7	1.57	879
T_{amb}	100	7	0.58	520
	105	7	0.59	521

To examine the different volumetric flows in the adsorber that will provide the lower gas consumption, were taken the results of this analysis then fixed the values of the condensation, regeneration and evaporation temperatures equal to 30 °C, 7°C and 100 °C, respectively, keeping the hot water tank volume equal to 7m^3 and the volumetric flow of the solar collectors equal to 0.0004 m^3 s^{-1}.

The results of the simulations are shown in the in the Table 4 and in the Figures 6 and 7 (Ribeiro, 2011).

Tab.4: COP and SCP for different water flow rates in the adsorber.

Volumetric flow in the adsorber	COP	SCP (W Kg^{-1})
0.0001 m^3 s^{-1}	***1.81***	***499***
0.0002 m^3 s^{-1}	1.84	535
0.0003 m^3 s^{-1}	1.87	619
0.0004 m^3 s^{-1}	1.90	750
0.0005 m^3 s^{-1}	1.93	928

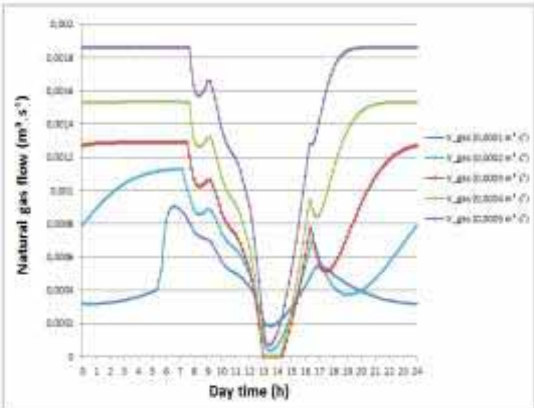

Fig. 6: Natural gas consumption for different values of the water flow rate in the adsorber.

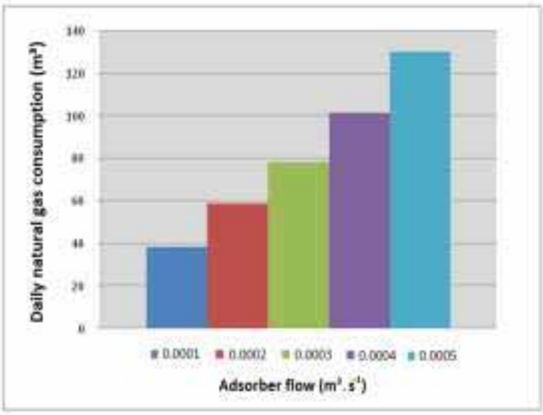

Fig. 7: Daily consumption of natural gas for different water flow rates in the adsorber, for the optimized system.

The comparison between the results in the Figures 6 and 7 shown that the value of the volumetric flow in the adsorber which provides the lower gas consumption is equal to 0.0001 $m^3\ s^{-1}$. Then, the parameters of the system considered optimized by the simulations are shown in the Table 5.

The Figure 8 shows the average water temperature (Tmed) in the hot water tank, for the solar collector volumetric flow of 0.0004 $m^3\ s^{-1}$ and the corresponding natural gas flow (v_gas). The Figure 9 shows temperature curves for the field of solar collectors (Tcol) and for the top (Tsup) and bottom (Tinf) of the hot water tank, during a day, both figures for the optimized system.

Tab. 5: Optimized parameters obtained from simulations.

Parameters	
Description	**Value**
adsorber water flow	0.0001 $m^3\ s^{-1}$
volumetric flow of the solar collectors	0.0004 $m^3\ s^{-1}$
hot water tank volume	$7 m^3$
chilled water temperature	$7 ^oC$
cold water temperature	$30\ ^oC$
water regeneration temperature	$100\ ^oC$

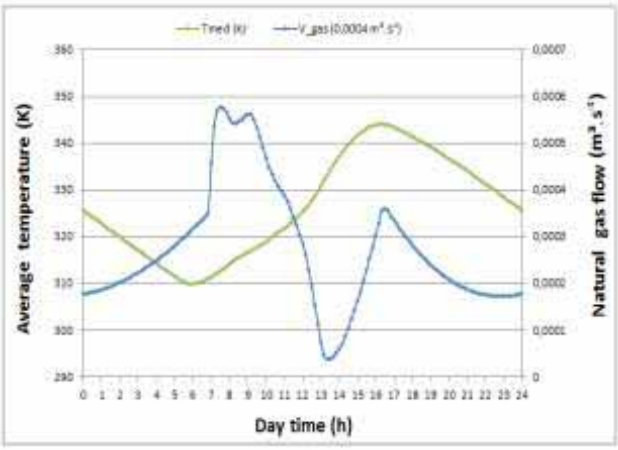

Fig.8: Average hot water temperature and the corresponding natural gas flow for a day.

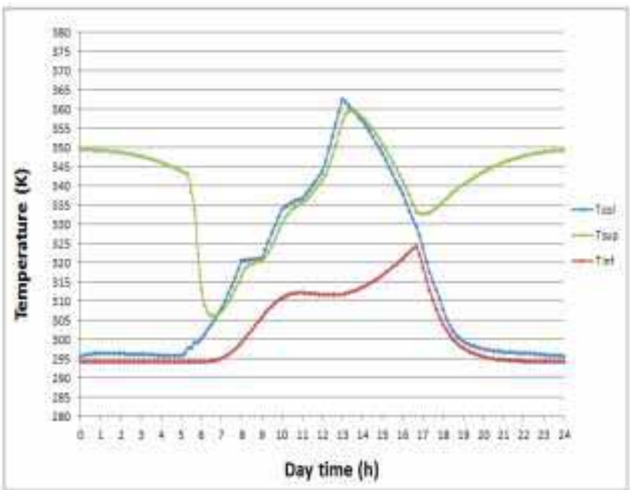

Fig.9: Daily variation of temperatures Tsup, Tinf and Tcol.

4.2. Analysis

The first results showed that the COP and the SCP depend on the water flow in the adsorber and on the regeneration, condensation and evaporation temperatures and are independent from the solar collector volumetric flow. Note that the parameter that plays the greater role on the COP and the SCP is the temperature of condensation (Table 3) (Ribeiro, 2011).

The maximum values of the COP and the SCP equal, respectively, to 1.93 and 928 W kg^{-1} (Table 3) were obtained for water flow in the adsorbers equal to 0.0005 m^3 s^{-1} and for the condensation, regeneration and evaporation temperature equal to 30°C, 100°C and 7°C, respectively.

The analysis of the curves in Figure 6 shows that the values of the natural gas flow for the corresponding values of water flows in the adsorbers are even higher than the values of the COP and the SCP are important. This somewhat surprising result for the solar systems seems to the use of the water storage tank, whose temperature of the upper part determines the amount of energy supplied by the auxiliary source, specifically the gas heater. This result is corroborated by the evolution during a day of temperatures in the top (Tsup) and in the bottom (Tinf) of the tank, as well as the temperatures in the solar collectors (Tcol) (Figure 9).

Figure 7 shows that the optimal water flow rate in the adsorbers for a minimum gas consumption is 0.0001 m^3 s^{-1}, with corresponding COP and SCP of 1.81 and 499 W kg^{-1}, respectively.

5. Conclusions

Many simulations were performed using the ADSOL program to analyze the influence of the main system operating parameters on the coefficient of performance (COP) and the specific cooling power (SCP).

The ideal water flow rates in the adsorbers and in the solar collectors were respectively 0.0001 m^3 s^{-1} and 0.0004 m^3 s^{-1}, respectively. These values were obtained for evaporation, condensation and regeneration temperatures respectively of 7°C, 30°C and 100°C, with the minimum gas consumption and corresponding COP and the SCP of 1.81 and 499 W kg^{-1}, respectively.

For improving the simulation results, a non-stratification condition for the storage tank should be considered in the model.

References

Domingos, P.V.S., Riffel, D.B., Veloso A.C.R., Ribeiro, C.M.C., Belo, F.A., Leite, A.P.F, 2010. Numerical simulation of the regeneration system of an adsorption air conditioning based on a high efficiency solar collectors field (in Portuguese), Proc. of the IV Solar Energy Latin American Conference (IV ISES_CLA – regional conference), Cuzco, Peru, 1-5.11.2010.

Duffie, J.A., Beckman, W.A., 1980. Solar Engineering of Thermal Processes, New York: J. Wiley & Sons.

Leite, A.P.F., Belo, F.A., Grilo, F.A., M.B., Andrade, R.R.D., 2003. Experimental evaluation of a multitubular adsorber covered by a high efficiency transparente insulation material (in Portuguese), Proc. of the VI Iberoamerican Congress of Mechanical Engineering (CIBEM6), Coimbra, Portugal, 15-18 Oct., , Vol. I, pp. 253-258.

Leite, A.P.F., Belo, F.A., Grilo, F.A., M.B., Andrade, R.R.D, Meunier, F., 2005. An improved multi-tubular solar collector applied to adsorption refrigeration, Proc. of ISES Solar World Congress, Orlando, Florida, USA, 6-12 Aug.

Leite, A.P.F., Riffel, D.B., Ribeiro, C.M.C., Belo, F.A., Domingos, P.V.S., Sarmento, D., Soares, M.B., Nascimento, L.J.L., 2011. A hybrid solar-gas air conditioning system based on adsorption and chilled water storage, Proc. of the World Renewable Energy Congress 2011(WREC2011), Linköping, Sweden, May 8-13.

Ribeiro, C.M.C., 2011. Post-doctoral report for CNPq Brazilian Agency. Activities of a research stage at the au LAMPS Laboratory at the Université de Perpignan Via Domitia, March-April, Perpignan, France.

Riffel, D.B., Leite, A.P.F., Belo, F.A., 2007. Simulation of the heat provided by flat plate solar collectors to a stratified cylindrical storage tank (in Portuguese), Proc. of the I Brazilian Solar Energy Congress, 13-17 nov., Fortaleza, CE.

Riffel, D.B., 2008. Estudo Teórico e Experimental da Dinâmica e da Otimização de Refrigeradores Térmicos por Adsorção, Tese de Doutorado (Eng. Mecânica), PPGEM/UFPB.

Riffel, D.B., Belo, F.A., Leite, A.P.F., 2009. Heat and mass recovery in an activated carbon-methanol adsorptive chiller, Proc. of COBEM 2009 - 20th International Congress of Mechanical Engineering, November 15-20, Gramado, RS, Brazil.

Riffel, D.B., Wittstadt, U.,Schmidt, F.P., Nunez, T., Belo, F.A., Leite, A.P.F, Ziegler, F., 2010a. Transient modeling of an adsorber using finned-tube heat exchanger, International Journal of Heat and Mass Transfer, Volume 53, Issues 7-8, March 2010, 1473-1482, ISSN 0017-9310.

Riffel, D.B., Belo, F.A., Leite, A.P.F., 2010b. Optimization of an adsorptive chiller using a statistic model (in Portuguese), Climatization & Refrigeration, April 38- 45.