NEW DEC OPEN CYCLE FOR AIR CONDITIONING BASED ON FIXED COOLED ADSORPTION BEDS AND WET HEAT EXCHANGERS

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ABSTRACT

In this work, a new solar Desiccant Evaporative Cooling (DEC) concept is presented. In the proposed system, two fixed packed desiccant beds of silica gel, operating in a batch process, are used as an alternative solution to the common adsorption rotor for dehumidifying outside air.
As well known, adsorption heat due to water condensation considerably reduces the dehumidification capacity of the desiccant material, causing inefficiencies in performance.
The aim of the work is to overcome the mentioned intrinsic thermodynamic limit of the adsorption rotor technology. The proposed core component is a fin and tube heat exchanger, commonly used in several air conditioning applications, wherein the spaces between the fins are filled with silica gel grains. Therefore, the adsorption material is cooled through a water loop in connection with a cooling tower. An important feature of the system is the adsorption storage capacity, this is due to the high amount of desiccant material available.
An indirect cooling process of the air is then realized by means of two wet evaporative heat exchangers connected in series, with continuous humidification of the secondary side.
The thermodynamic cycle is first presented and simulation results are shown and discussed.
Possible applications may concern compact roof-top units as well as common AHUs.

1. Introduction

The Solar DEC technology is an interesting and fascinating solution for applications in building air conditioning. Thermally driven open cooling cycles are based on a combination of evaporative cooling and adsorption processes. In the standard solar desiccant cooling cycle, solar energy is used to regenerate a desiccant material that dehumidifies moist air by vapour adsorption; the resulting dry and warm air is first cooled in a sensible heat exchanger (usually rotating) and then optionally further cooled in a direct evaporative cooler. The technique uses water as a refrigerant, combining different elementary treatments in moist air (dehumidification, sensible cooling and evaporative cooling), both in process and exhaust air streams.
In common DEC air handling units, desiccant rotors are normally used. However, the adsorption process realized by means of desiccant rotors presents the disadvantage of causing a temperature increase of the desiccant material. This phenomena is caused by the release of adsorption heat due to water condensation in the desiccant material and by the carry-over of heat stored in the desiccant material from the regeneration section to the process section.

An increase of the desiccant material temperature is responsible for lower dehumidification capacity and higher regeneration temperatures required, with a consequent negative impact on the overall system efficiency. Other studies on technical solutions, that permit the simultaneous heat and mass transfer have been carried out by other authors [9, 10].
Moreover, desiccant rotor technology doesn't present the opportunity to store adsorption capacity into the desiccant material. They are generally built to host a relatively low mass of adsorbent. Therefore the only option for energy storage can be related to the driving fluid, i.e. water heated by a solar plant. Since water storage requires investment costs, several restrictions have to be considered in storage sizing. In addition, the use of hot air as regeneration fluid is suitable only with systems without storage.
These two issues have been handled in liquid DEC systems, where the adsorbent is utilized in a liquid solution with water. In such systems, the storage effect is associated to the dehumidification capacity of a dried solution contained in a tank. However liquid DEC systems present some problems related to the increase of parasitic electricity consumption, system complexity and durability of hydraulic components due to corrosion caused by the water-adsorbent solution.
The second core component of a standard DEC cycle is the rotating heat exchanger which is associated to the humidifier set on the return air path, both used to realize the indirect evaporative cooling process. Nevertheless, the indirect cooling process obtained using the mentioned components can only partially exploit the cooling potential, due to the wet bulb temperature of the secondary air stream.
In addition, a carry-over of water vapor from the return to the process air side of the desiccant AHU can often occur. Detailed humidity measurements up- and downstream of the rotating heat exchanger have shown that the dehumidification capacity of the whole desiccant unit can be strongly affected by this process, leading to a greater use of the auxiliary cooling coils [2].

2. Description of component development

In this work a new solar DEC concept is presented with the aim to overcome some of the limits described for the standard DEC cycle.
The first important aspect which differentiates the proposed solar DEC cycle from the traditional one is related to the use of an innovative component for the air dehumidification. The proposed component is a fin and tube heat exchanger, commonly used in several air conditioning applications wherein the spaces between the fins are filled with silica gel grains.

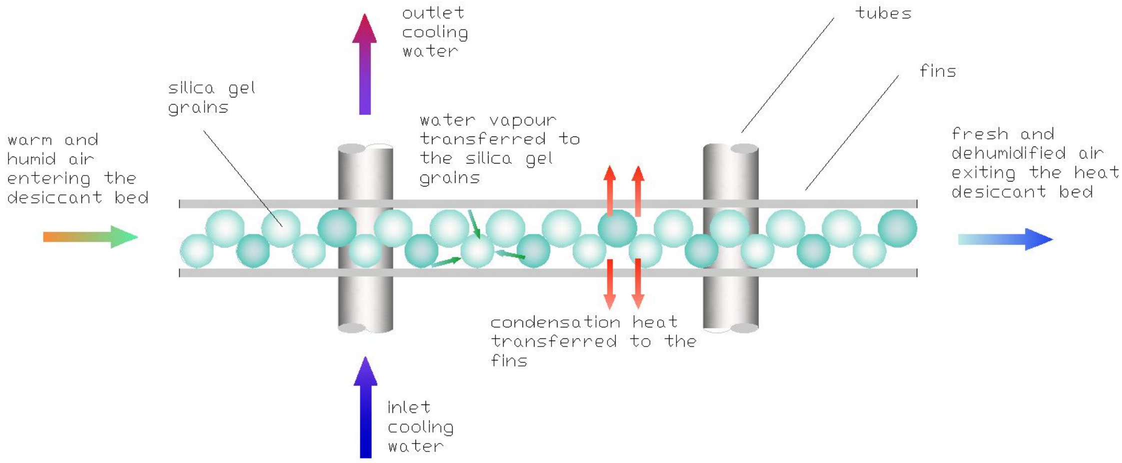

Figure 1: Scheme of the cooled adsorption bed

Therefore, thanks to the exchange surface of the heat exchanger, the adsorption material can be cooled through a water loop in connection with a cooling tower. The continuous dehumidification process of the process air is then realized using two beds in a batch operation.
A scheme of the process realized in the adsorption bed is shown in Figure 1.
First of all it must be highlighted that its particular geometry allows a simultaneous mass transfer between the moist air and the adsorbent media and heat exchange between the air and the water flowing into the heat exchanger tubes.
In the framework of other works carried out by the authors on the same topic, an experimental set-up has been realized in order to investigate the performances of the component. The tested desiccant bed, containing 18 kg of silica gel, has been designed for a maximum flow rate of 300 m^3/h. Tests have been carried out looking at the dehumidification and cooling performances of the adsorption bed. Measurements related to the adsorption process were conducted both on the air and water side in order to better study the heat rejection process.
Experimental data showed that high air dehumidification performances can be obtained, both in terms of total mass of water adsorbed and favorable time dependence of adsorption capacity. For typical summer outside air conditions, values of outlet air humidity ratio ranged from 4-5 g/kg at the beginning of the adsorption cycle to 10-12 g/kg at the end of the cycle when the adsorption process is stopped and regeneration is started.
In general, the advantages of using the proposed component in comparison to the common desiccant rotors can be summarized as follows:

- cooling of the desiccant material during the adsorption process is possible, allowing high dehumidification performances of the desiccant bed and in general better overall energy performances of the system;
- high adsorption capacity can be achieved, strongly reducing the necessity for thermal storage;
- adsorption and desorption processes happen in different times, permitting a better control of the dehumidification process;

The experimental results will be published in the future by the same authors.
Further experimental tests have been conducted in order to investigate the performances of the wet heat exchangers in series connection and with continuous humidification of the secondary side [3,4].
The system consists of a common cross flow plate heat exchanger operated under wet conditions. The surface of secondary flow air channels (return air from the building) is wetted by water spraying, such that the water evaporates into the cooling air and decreases the temperature of the heat exchange surface. The spray nozzles being used have relatively large orifices and operate with low water pressure [1]. Process air flowing in the primary airflow channels is cooled down due to the lower temperature surface of the separating wall of the heat exchangers. The temperature of the saturated air on the wet air side depends on the local wet-bulb temperature of the air stream that gradually increases during the humidifying process.
Tests were aimed to compare the cooling performances in dry and wet operation. A particular focus was the assessment of the variation of the flow rate of secondary air stream for the same flow rate of the primary air side. This is an important issue since in the proposed system configuration secondary air flow rate in the wet heat exchangers is much smaller than the one on the primary side. It has been observed that, for 50% of the mass flow rate ratio, efficiency turns out to be about 85% of the value obtained with a mass flow rate ratio of 100%. A value of about 65% was registered for a mass flow rate ratio of 30%.

3. Description of the new DEC cycle

The proposed new DEC cycle is mainly based on the use of two fixed packed desiccant beds of silica gel, operating in a batch process, and two wet evaporative heat exchangers connected in series. The air flow rate passing the adsorption bed is about 40% of the one delivered to the conditioned space. This value corresponds to the flow rate percentage passing the secondary side of the heat exchanger, in order to maintain supply and return air flow rates in balance.
The air passing the adsorption bed is simultaneously dehumidified by the desiccant material and cooled by the water loop connected with the cooling tower (1-2).
A system of air dumpers provides the commutation between the two adsorption beds in order to guarantee a continuous dehumidification process.
During the adsorption cycle of one bed, regeneration of the desiccant material of the other bed can be operated. The regeneration is done by means of hot air provided by solar air collectors (1-7-8). No auxiliary device is included.
System is operated in mixing mode, that means only 40% of the total flow rate is outside air. The mixing point (3) is downstream to the adsorption process so that only a portion of the total flow rate is dehumidified, passing the adsorption bed. This solution permits to limit the pressure drop across the adsorption beds which is below 100 Pa and to avoid contamination of the desiccant material due to possible pollutants in the return air. The humidity ratio at the mixing point corresponds to the one of the supply air.
The mixed air is then cooled through a sensible heat exchange in two wet heat exchangers reaching the supply conditions (4). A fraction (40%) of the flow rate exiting the primary side of the wet heat exchangers is drawn into the secondary side and maintained close to saturation line (4-5) [5].

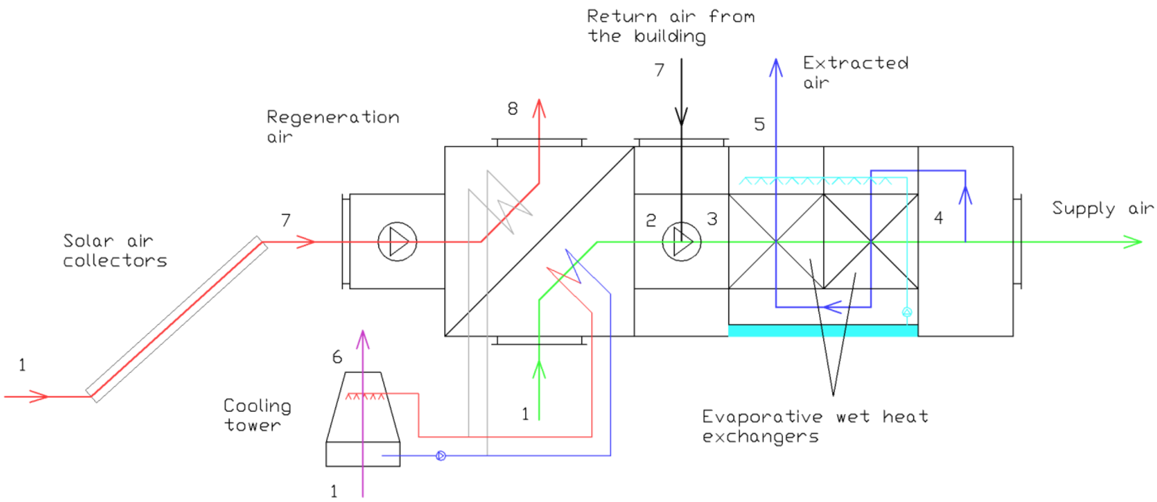

Figure 2: Scheme of the DEC system

Electricity consumptions of the system are related to the use of two fans, two pumps and a cooling tower. Figure 3 shows on the psychrometric chart the mentioned air processes for typical summer conditions of outside air (T=36°C and x=16 g/kg) and average performances of the desiccant bed. It has to be noted that, since the system works in a batch process, the thermodynamic transformations data would change through the adsorption and desorption cycle.

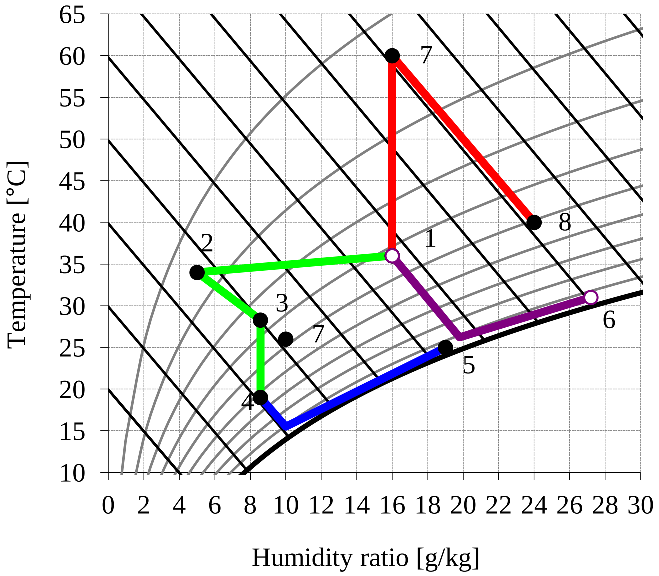

Figure 3: Thermodynamic cycle of the DEC AHU – Process air (green), secondary air entering the heat exchanger (blue), cooling tower (purple) e regeneration (red)

4. Results of the TRNSYS simulations

The cycle described above was simulated with the software TRNSYS with the aim to assess the energy performance of the system for a selected case study.
According to the mentioned experimental results, which were carried out on the desiccant bed and the wet heat exchanger, some new TRNSYS types were created. In particular, for the adsorption bed a semi-empirical model (Type 165) partially based on the approach suggested by Pesaran and Mils was created [6]. For the simulation of the wet heat exchanger, a modification of the Type 757 was necessary in order to correctly assess the influence of the variation of the mass flow rate ratio between the primary and secondary side of the heat exchanger. Simulation time step is one minute in order to efficiently describe the dynamic effect of the desiccant beds wherein the commutation time between adsorption and desorption phases is fixed and equal to 0.25 h.
The system has the configuration described above and is connected to a conditioned space of about 1200 m^3 used as a classroom. Occupation profile is 150 persons from 8:00 to 13:00, 20 from 13:00 to 15:00 and 100 from 15:00 to 18:00. The weather data file used is related to the location of Palermo (South Italy) 38°6' N 13°20' E.
The total AHU flow rate delivered to the conditioned space is 8300 m^3/h which corresponds to an air change of 6.95 1/h. Flow rate of fresh outside air passing the adsorption beds is 3300 m^3/h.
Maximum sensible and latent loads including internal gains, ventilation and infiltration, are respectively 25 and 51 kW. Each adsorption bed has a total volume of 0.3 m^3 and contains about 115 kg of silica gel in grains. A surface of 46 m^2 of solar air collectors provides the heat necessary for the regeneration of the desiccant material. Solar collector flow rate is 4200 m^3/h.
The maximum electricity consumption for the fans and the pumps is approximately 4,5 kW when operated at full speed. The cooling power of the AHU can be varied controlling the speed of the process air fan.
The following figures show the results of the simulation carried out. It was decided to report only five days of operation (19th - 23th July) to focus on instantaneous system performances during typical hot and humid summer days.

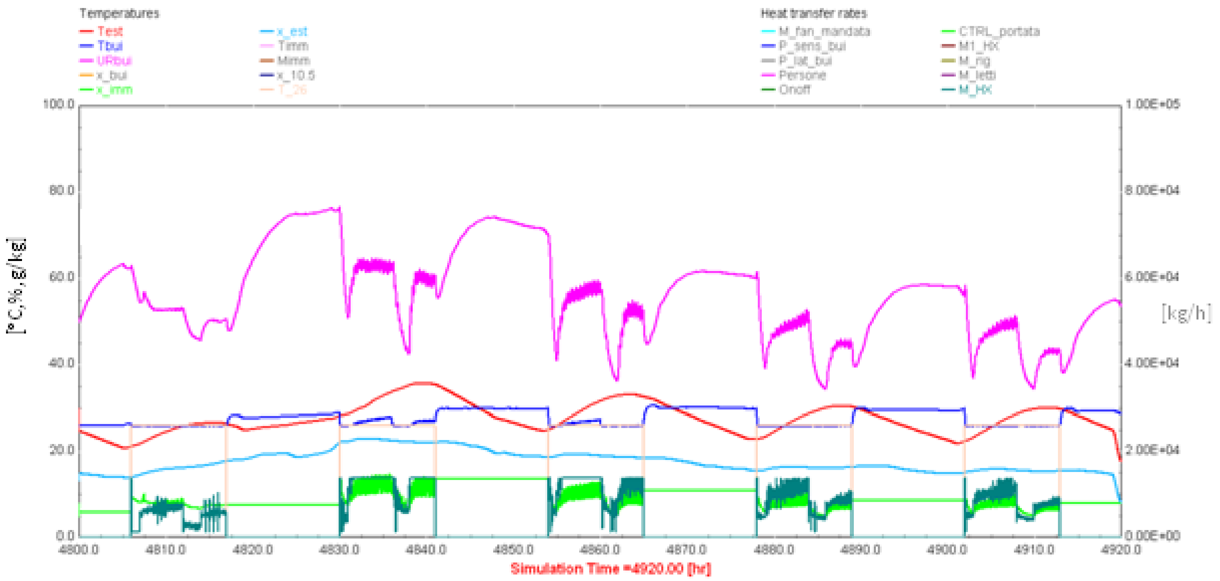

Figure 4: Temperature and humidity of the air in the conditioned room

Figure 4 shows temperature and relative humidity of air in the conditioned space. In general, it can be observed that the desired indoor conditions (T=26°C and RH=50%) are satisfied. Taking under consideration the second day, where outside temperature of nearly 36°C (T_{est}) and humidity ratio (x_{est}) is 22 g/kg are observed, internal maximum temperature (T_{bui}) and relative humidity (UR_{bui}) are respectively 27.8°C and 64%. It can be noted that, during the second and third day, the control system maintains the fan speed at the maximum flow rate, whereas in the other days only a few times the maximum value is reached.

In Figure 5 the inlet and outlet temperatures of the main components of the AHU are reported. Supply temperature (clear green) ranges from a minimum of 17.2 °C to a maximum value of 23.7°C depending by the wet bulb temperature of the supply air (dark green) exiting the heat exchanger which is partially drawn to its secondary side. Maximum regeneration temperatures are quite low and in the range of 55°C permitting the efficient use of the solar air collectors.

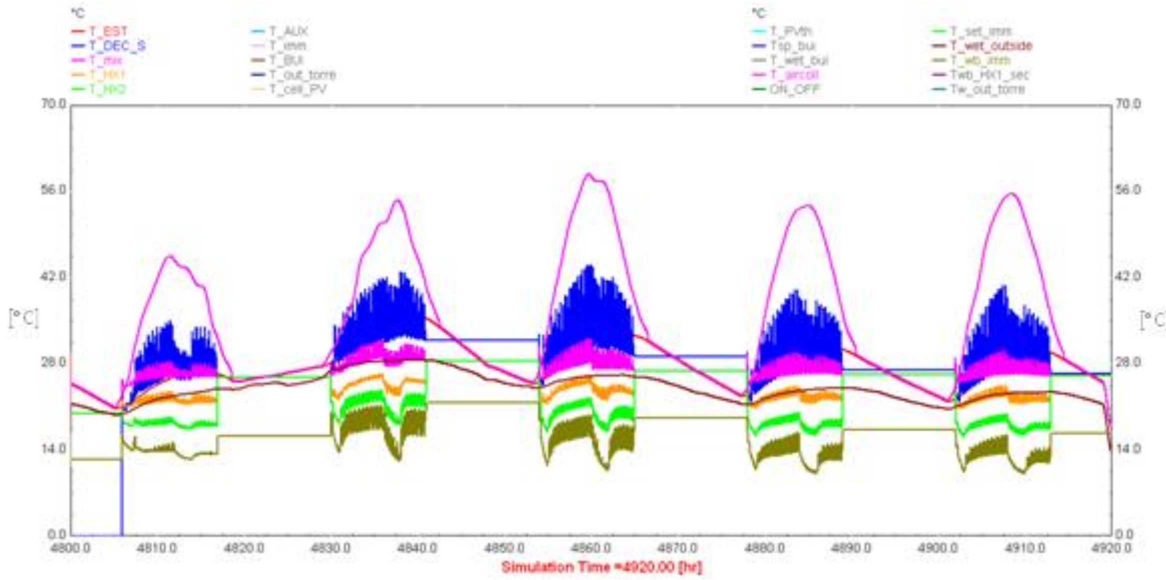

Figure 5: Temperatures in the AHU components

Finally Figure 6 shows the cooling power of the AHU ranging between 48 and 90 kW for the second day of operation with an average value of the global electrical COP of about 15. The daily average value of the thermal COP, calculated including the evaporative cooling effect, ranges from a minimum value of 1.4 for the first day and 3 for the second day of operation.
Efficiency of wet heat exchangers, considered as a single component, ranges from 60 to 65%. Even if this value seems not to be very high, low temperatures of supply air can be reached thanks to the low wet bulb temperatures of secondary air and the series connection of the wet heat exchangers.

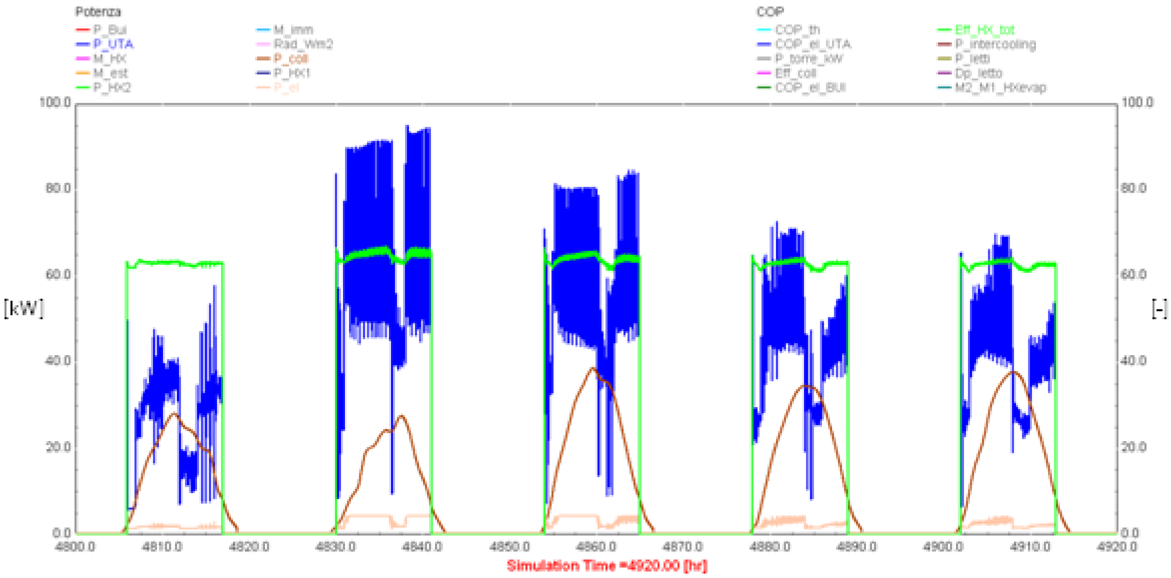

Figure 6: Cooling power of the AHU (blue) and solar heat production (brown) in kW, efficiency of wet heat exchangers (green)

5. Conclusions

In this paper, an innovative solar DEC concept using a combination of fixed desiccant beds packed with silica gel and two wet heat exchangers is presented and analyzed.
The aim of the work is to overcome some intrinsic thermodynamic limits of the adsorption rotor technology. As is well known, adsorption heat due to water condensation sensibly reduces the dehumidification capacity of the material, causing lower system performance.
The component proposed for the air dehumidification is a fin and tube heat exchanger, wherein the spaces between the fins are filled with silica gel grains.
The second core aspect of the cycle is the combination of two wet heat exchangers connected in series and with continuous humidification of the secondary side. A fraction (40%) of the flow rate exiting the primary side of the wet heat exchangers is drawn into the secondary side and maintained close to saturation. This solution permits to efficiently exploit the indirect evaporative cooling potential, achieving low supply temperatures.
Simulation results carried out for the case study, have shown that the simultaneous mass and heat transfer permits high dehumidification capacity, causing an increase of the global system performances. A daily average COP of 15 was calculated for a hot and humid day (second day). Daily average thermal COP range from 1.4 to 3. Supply temperature range between 17.2 °C and 23.7°C, dependent on the wet bulb temperature of the air entering the secondary side of the heat exchanger. Simulation results obtained on the whole system operation are extremely encouraging, Further developments of the system control strategy are being explored.

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Pietro Finocchiaro (Catania, 1975) Mechanical Engineer, PhD in Applied Physics at the University of Palermo. His researches have been focused mainly on solar cooling technologies, dealing in particular with desiccant and evaporative cooling (DEC) cycles working with solid adsorbent materials. Since 2007 he joins experts research groups such as Task 38 of the International Energy Agency, whose activities are now continuing in the Task 48, contributing in the development of standards for the monitoring of solar cooling systems, new components and system configurations. He cooperates in many research projects dealing with the use of renewable energy in the building sector, participating to many national and international scientific conferences in the field of solar. He has about 30 publications on scientific conference proceedings and ISI Journals.

Marco Beccali (Palermo,1967), Civil Engineer (1991), PhD in Energy and Environmental Technologies (1994), is Associate Professor on Applied Physics and HVAC Systems at University of Palermo, Italy. His main research interests are: renewable energy systems implementation and diffusion, urban energy planning, building physics, thermal comfort techniques and strategies. In the last twelve years he has been working mainly on researches of Solar Heating and Cooling systems, especially in Open Cycles for Air Conditioning. He has participated as expert and sub activity co-ordinator at the IEA-SHC TASK 25, 38 and 48. He was member of many Conferences Scientific Committees and Chairman of the 3° OTTI International Conference of Solar Air Conditioning held in Palermo in 2009.