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AIR COOLING AND DEHUMIDIFICATION WITH A ZEOLITE COATED HEAT EXCHANGER REGENERATED BY SOLAR THERMAL ENERGY

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ABSTRACT

This paper presents some experimental results of a new device for low energy/low exergy air conditioning system. The device can realize both dehumidification and sensible cooling of external air, and it is designed for very low pressure drops, drastically reducing the electricity consumption for the driving fans. It is composed by a finned coil heat exchanger, coated with a SAPO-34 zeolite layer, that handles both heat and mass transfer in a single component. During the adsorption a cold water flow at 20 °C circulates through the coil, cooling the air and realizing in a single step a complete air-treatment. Hot water produced with evacuated solar collector is then used to regenerate the zeolite.

Keywords: adsorption dehumidification, solar cooling, adsorption heat exchanger, experimental

1 INTRODUCTION

Cooling demand for air conditioning (AC) has continuously increased in the last decades. This because more and more buildings are provided with space cooling system to satisfy indoor comfort demand during warm and hot season (Werner, 2016) (Jakubcionis and Carlsson, 2017). Solar cooling is an alternative solution to traditional system that may attenuate the increase of electric consumptions associated to the cooling demand, and one of the simplest technology are the Desiccant Evaporative Cooling system (DEC). They are thermally-driven open cooling cycle, based on evaporative cooling and adsorption processes. In this technology, the dehumidification process is commonly carried out using desiccant rotors impregnated or covered by adsorption material (i.e. silica gel or lithium chloride) (Daou et al., 2006). Warm and dry air obtained from this step, is typically cooled using an indirect evaporative cooling module. Solar energy is used to regenerate the desiccant material, that dehumidifies moist air adsorbing vapor. Alternative configurations of the dehumidification component, the adsorption heat exchangers (ADS-HX) were explored (Finocchiaro et al., 2016), (Simonetti et al., 2016, 2017), (Zhao et al., 2016). These are static components in which there is the contemporaneous exchange of heat and mass between the air and the sorption material, and the heat between the adsorption material and a secondary fluid vector. The disposition of the adsorption material in a finned coil heat exchanger, typically used in air conditioning, can be different: surface coating on the fin or granular dispersion in the void volume. The goal of this research is to explore the use of renewable thermal energy, at temperature level between 55-80°C, to satisfy the latent load of the air conditioning using this type of technology in alternative of vapor compressor chillers. Savings in electricity consumption are attended.

2 METHODS

2.1 Adsorption heat exchanger

The component here presented is a fin and tube heat exchanger, typically used in HVAC system, in which all the exchanging surface, by tubes and fins, is coated with a zeolite. The advantage of this component, with respect to fixed packed bed (Finocchiaro et al., 2016), is the possibility to have contemporaneous heat and mass transfer between the air, the adsorptive mass, and a secondary thermal vector fluid. The two working mode are represented in the scheme of Figure 1. During the **regeneration**, the heat is provided by hot water flow inside pipes of the heat exchanger. Then water vapor, previously captured by the zeolite, is released and transported by the air flow. The operation continues until the adsorption mean reach a sufficient level of drying to start the successive phase of dehumidification. After this operation the hot water flow is stopped and substituted by a cold water flow, circulating through the pipes of the same heat exchanger. This phase is the **cooled adsorption**: water vapor capture by zeolite reduces the moisture content of the air and produces heat, that is comparable with the latent heat of water evaporation. Previously tests of this component showed that the residual heat coming from the regeneration phase of the component influences significantly the dehumidification performance during the adsorption (Simonetti et al., 2016). This aspect combined with the heat generated by the adsorption phenomena result in low performance of the system. By cooling the coil during the adsorption, the increase of air and zeolite bed temperature is avoided and the material operates at its higher water adsorption capacity (Figure 2). Temperature level of water and flow rate regulates the equilibrium condition and the final temperature of the air at the outlet of the heat exchanger. Controlling these parameters, different air outlet condition can be achieved.

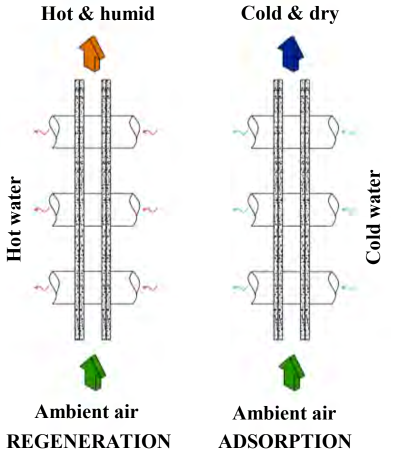

Figure 1. Scheme of the regeneration and adsorption phase of the zeolite SAPo-34 heat exchanger.

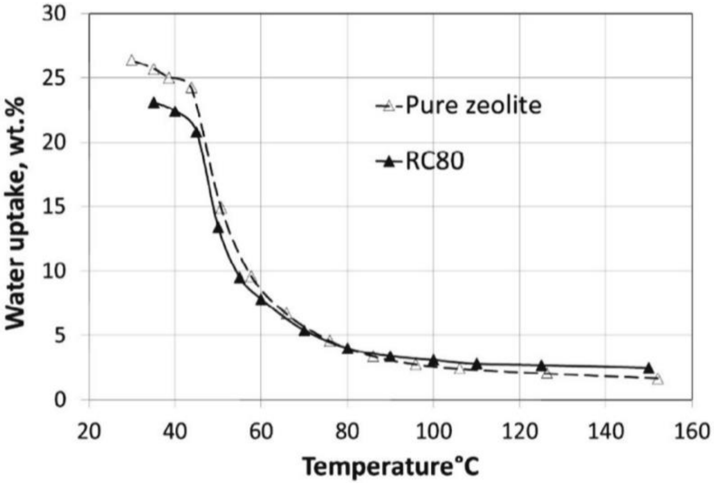

Figure 2. Comparison of the adsorption isotherm between pure zeolite SAPO-34, and the mixture coated on the surface of the heat exchanger (Simonetti et al.,2016) .

The type of zeolite used for this case study is the SAPO-34. Such material, belonging to the (silico) aluminophosphate family, shows a regular pores system, a three-dimensional network similar to zeolites and unusual adsorption properties regarding polar molecules, typically exhibiting a type V water vapor adsorption isotherm (Ng et al., 2008). These properties result in moderately low regeneration temperature (60‑100 °C) and a reduced desorption heat, while maintaining high performance within the adsorption cycle (Henninger et al. 2010). The coating procedure of the ADS-HX involves different steps (Simonetti et al.,2016), that influences the properties of the adsorption material. In particular the adsorption properties are slightly reduced respect to the pure SAPO-34, as showed in Figure 2. The final result of this manufacturing process is showed in Figure 4 and Figure 5.

2.2 Experimental set up

The experimental facility consists of two AHUs (Air Handling Units) that can process air flow rate (Q) in the range 100 ÷ 1500 m^3/h (measured with calibrated flanges) controlling outlet temperature and humidity. Air temperature (T_a), humidity (X_a) and water temperature (T_w) sensors are distributed along the adsorption unit, as showed in Figure 3. In Table 1 the list of sensors and their accuracy employed in the experimental activity is shown. The heat for regeneration is provided with 10 m^2 of evacuated solar thermal collectors and into a 500 lt thermal storage, equipped with an auxiliary electrical resistance of 3 kW. In Table 2 are reported the geometric characteristics of the finned coil heat exchanger, and the zeolite coating thickness is lower than 1 mm.

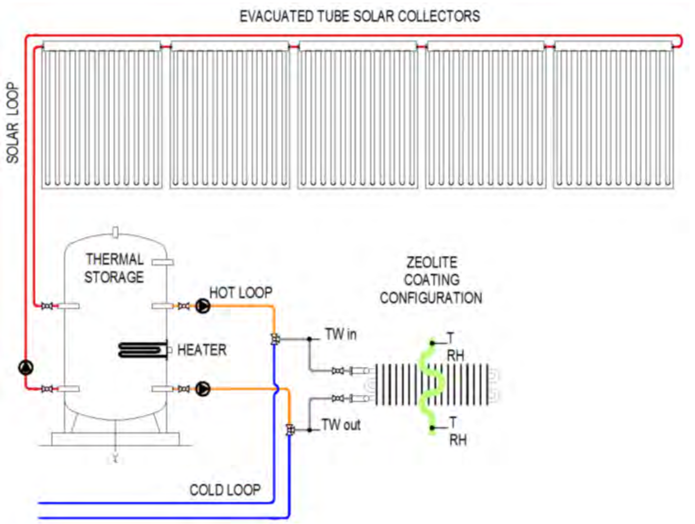

Figure 3. Scheme of the experimental set up for the test of the ADS-HX in laboratories of the Energy Department of Polytechnic of Turin.

Table 1. Sensor types and related accuracies.

Sensors	Accuracy	Unit
Air Pressure	± 0.2%	Pa
Air Temperature	± 0.4°C	°C
Water Temperature	± 0.3°C	°C
Relative Humidty	± 2%	%
Water flow rate	± 3%	kg/s
Air flow rate	± 7%	m^3/h

Table 2. Dimensions of the finned coil

	d	n	p	L	D	H
	mm	-	mm	m	m	m
Fins	-	56	8	-	0.15	0.54
Tubes	15	24	-	0.45	-	-
Battery	-	-	-	0.45	0.10	0.54

Figure 4. Picture of the SAPO-34 ADS-HX

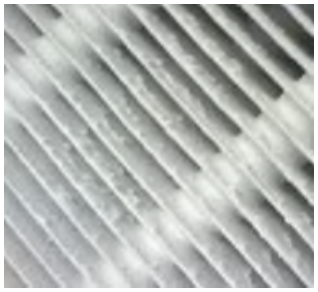

Figure 5. Zeolite coating on the HX

2.3 Test procedure

The tests aim to explore the transient dynamics of adsorption/regeneration cycle measuring air and water operational parameters at growing air flow rate. At the begin of each adsorption test the zeolite starts in a dry initial condition. The AHU prepares the air at the desired temperature and moisture content. Then adsorption tests start cooling down the zeolite with the cold-water loop; during this phase the air flow is mechanically driven by the fan of the AHU. When the air dehumidification goes below 1 g/kg the adsorption test ends. Then the fan of the AHU is stopped, and the water flow switched from cold to the hot circuit connected to the storage, fed by solar collectors. The same criteria of adsorption phase is used to stop the desorption one During the regeneration natural ventilation of the heat exchanger occurs, thanks to the positive buoyancy, thermally generated. Air temperature and humidity as hot and cold water temperature and air pressure drops are continuously monitored and logged.

3 RESULTS

First, the adsorber air pressure drops were measured at different temperature (15 to 35 °C) ranging air velocity (v) from 0.2 to 1.6 m/s: the higher value is lower than 12 Pa (Figure *6*). Further, three different operational tests have been carried out: air flow rate ranges from 220 to 430 m^3/h; average regeneration temperature is 60°C; average cooling water is 20 °C; the water flow was around 2.7 liter/min throughout regeneration, and 22.4 during adsorption. Other information, such as operation time and moisture content are reported briefly in Table 3. The test 2 is depicted in Figure 7, to illustrate the behavior of all the physic parameters monitored during adsorption and regeneration.

Table 3. Average and deviation of the input test condition

	phase	**time**	**Q**	**$T_{a\text{-}in}$**	**$RH_{a\text{-}in}$**	**T_w**
		min	m^3/h	°C	%	°C
Test 1	Ads	27	$196.2_{\pm 13.4}$	$31.9_{\pm 1.0}$	$68.4_{\pm 6.1}$	$18.1_{\pm 0.4}$
	Reg	29	$67.4_{\pm 21.0}$	$28.7_{\pm 1.0}$	$48_{\pm 6.9}$	$61.5_{\pm 3.7}$
Test 2	Ads	23	$331.1_{\pm 7.1}$	$30.3_{\pm 2.5}$	$62_{\pm 11.5}$	$18.6_{\pm 0.3}$
	Reg	25	$67_{\pm 21.0}$	$29.7_{\pm 0.6}$	$30.5_{\pm 3.5}$	$63.1_{\pm 3.2}$
Test 3	Ads	15	$412.7_{\pm 4.0}$	$30_{\pm 1.9}$	$58.3_{\pm 8.8}$	$20.5_{\pm 2.0}$
	Reg	22	$83_{\pm 20.0}$	$29.8_{\pm 0.4}$	$27.4_{\pm 4.3}$	$62.7_{\pm 2.9}$

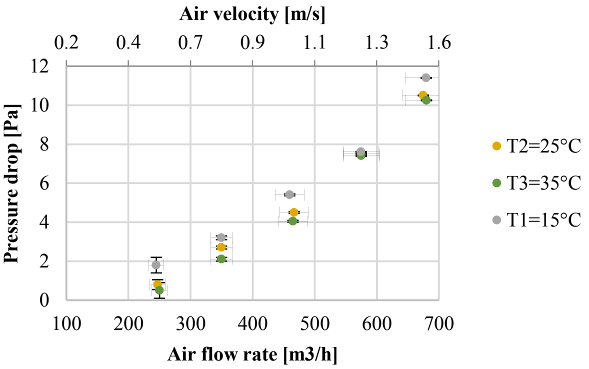

Figure 6. Zeolite SAPO-34 heat exchanger pressure drops

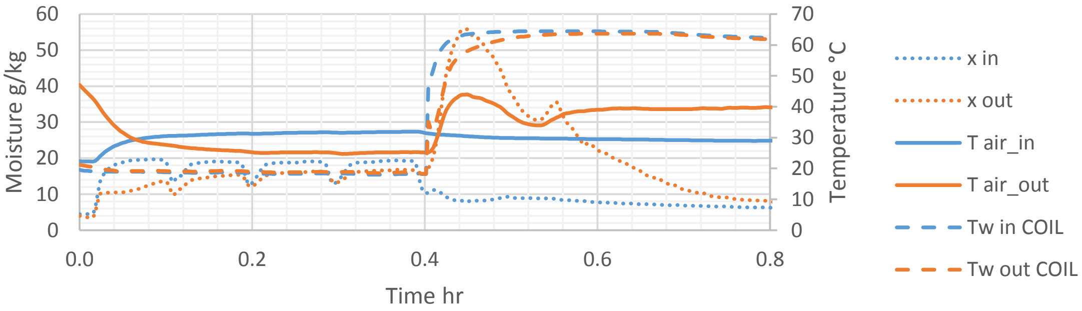

Figure 7. Behavior of the air and water physical parameters, temperature and moisture content, during an adsorption (time<0,4) and regeneration (time>0,4) test carried out on the adsorptive heat exchanger.

Adsorption had a duration of around 20 min, with an average dehumidification of 4 g/kg, and a maximum value of more than 8. Except for the initial transient, outlet temperature was always lower than the inlet. Regeneration had a similar duration, but with less than 1/5 of the adsorption air flow rate. Figure 8 and Figure 9 report the difference between a not cooled (with similar air inlet condition and flow rate of test n°2) and a cooled adsorption are showed. It can be observed how in the initial transient (t< 1min) the cooling operation results in a higher exploitation of the zeolite, showing higher moisture removal, and a fast heat removal shifting air temperature below the inlet condition in less than 5 minutes. Increasing air flow rate, from the first to the last test, with similar air inlet condition during adsorption, has two significant results: a reduction of the maximum value of air dehumidification (from more than 8 to 6.5 g/kg), and an increase of the slope of the curve, as can be seen in Figure 10. This leads to a progressive reduction of the duration of the adsorption phase, from 30 to around 20 minutes. All these characteristics are clearly depicted and summarized in Figure 11, in which the total thermal power (latent and sensible) exchanged between air and the ADS-HX is showed.

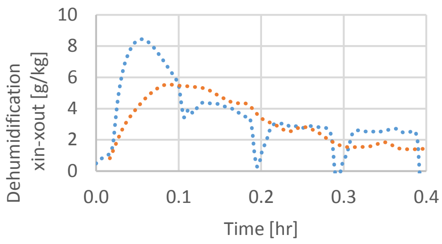

Figure 8. Differences on dehumidification curves in an adsorption test with and without cooling, at same air flow rate.

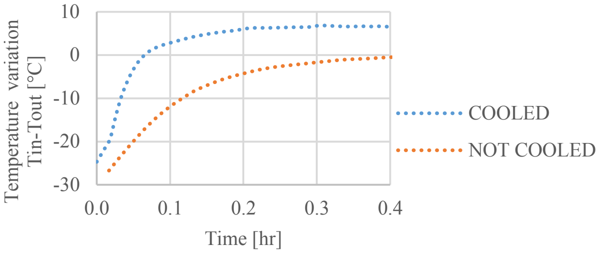

Figure 9. Differences on air temperature variation in an adsorption test with and without cooling, at same air flow rate.

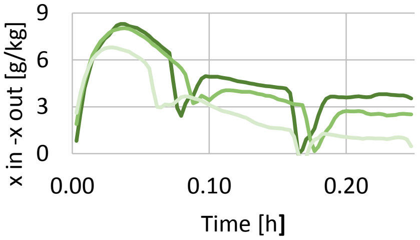

Figure 10. Effects of the air flow rate increase on air dehumidification during cooled adsorption, for the three different tests.

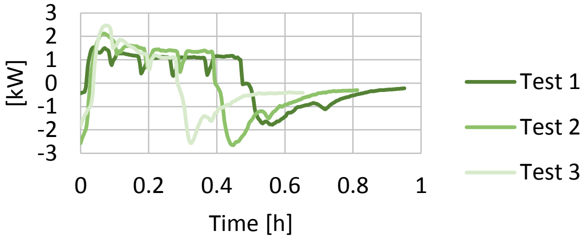

Figure 11. Thermal power exchanged between air and the ADS-HX during both adsorption (left part) and regeneration (right part), for the three different tests.

4 DISCUSSION

The integration of this component in traditional HVAC system (in particular for small size applications), to cool down and dehumidify humid air gives the possibility to directly exploit renewable energy. The low temperature of the hot source, 60°C, is compatible with the use of solar thermal systems to regenerate the component. In Figure 12 is compared the air transformation between the cooled adsorption and a typical condensing and re-heating process. Dehumidification by cooled adsorption ($\Delta h_{4\text{-}1}$ = - 37 kJ/kg) needs lower cooling energy at higher temperature ($T_{cold\ water}$=18-20 °C) than traditional system ($\Delta h_{4\text{-}1}$ = - 45,3 kJ/kg and $T_{cold\ water}$=7-12 °C). The temperature increase of the cold source enable the use of natural heat sink like groundwater. In order to guarantee a continuous supply service of cooling and dehumidification like in the graph, more components in parallel (at least two) have to be managed in a batch process. The frequency of switching between adsorption and regeneration is influenced by operational (temperature and vapor pressure) and geometric parameters such as the total exchange surface; the total amount of adsorbing mass; length of the exchange path. The optimization of these parameter need to be evaluated including the cost of the adsorbing material and installation costs related to the control system. A smarter geometric shape than the coated fin should lead to higher exchange surface per volume unit against a reduction of the manufacturing costs. Low switching frequency generally reduce the complexity of the control system resulting in a lean managing equipment.

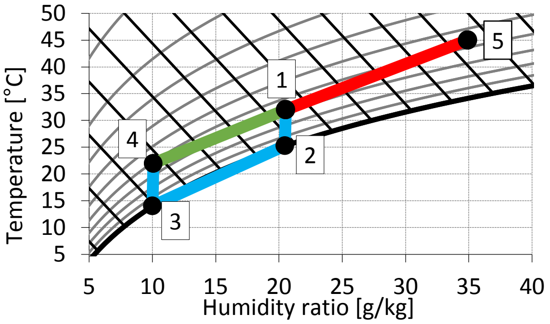

Figure 12. Comparison between cooled adsortpion with traditional systems.

5 CONCLUSIONS

The coated-coil configuration presented is able to exchange heat and mass with the same device. The tested prototype can sustain for around 20 minutes an average dehumidification effect in the range 7-5 g/kg. Cooling the adsorption phase increased the dehumidification effect by around 30%, with evident benefits for the outlet air temperature. Similar devices can be considered for future applications in air-handling units substituting electrical consumptions of traditional cooling technologies with a sustainable heat demand, provided by solar energy and natural sink. The development of the prototype leads to increase performances and cost in order to obtain a more feasible solution for commercial applications.

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