Water production from the atmosphere in arid climates using low grade solar heat

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Abstract

Water scarcity is a severe problem that involves large areas of the World. The possibility to extract water from atmosphere is more and more investigated as a fascinating solution to face this problem in arid climates. A day-night thermodynamic cycle is here investigated to produce water from air using low temperature heat in an adsorption bed typically used for air dehumidification in DEC systems. The system can be easily integrated with a solar thermal collector and waste heat at 50-80 °C. The preliminary results of the experimental tests of a prototype that gives the possibility to simultaneously exchange heat and mass through the adsorbing mass are here presented.

Keywords: Atmospheric water harvesting, adsorption material, solar energy, water production,

1. The problem of access to water resources

Water scarcity is not a new problem, but the rise of the fresh water demand in the last years poses this issue as the critical challenge for the next 20 years. The OECD Environmental Outlook 2050 estimates that by 2050 water demand will increase by 55%, BRICS and developing countries plays a fundamental role in this scenario: respectively with an increase by 700% and 400%. Main actors of this increase are the domestic, manufacturing and power sector, driven by the increase of population, evaluated up to 33%, that will be concentrated in developing countries. (UNESCO, 2015). Cities are the areas in which the water challenge will most be played: in 2014 54% of the global population lived in cities and by 2050 it will be more than 65% (UNDESA, 2014). This water demand is mainly satisfied by the extraction from the available surface and groundwater source, that are yearly recharged by the hydrologic cycle. Figure 1 depicts the world condition in 2015 in terms of water withdrawal as a percentage of the renewable resources.

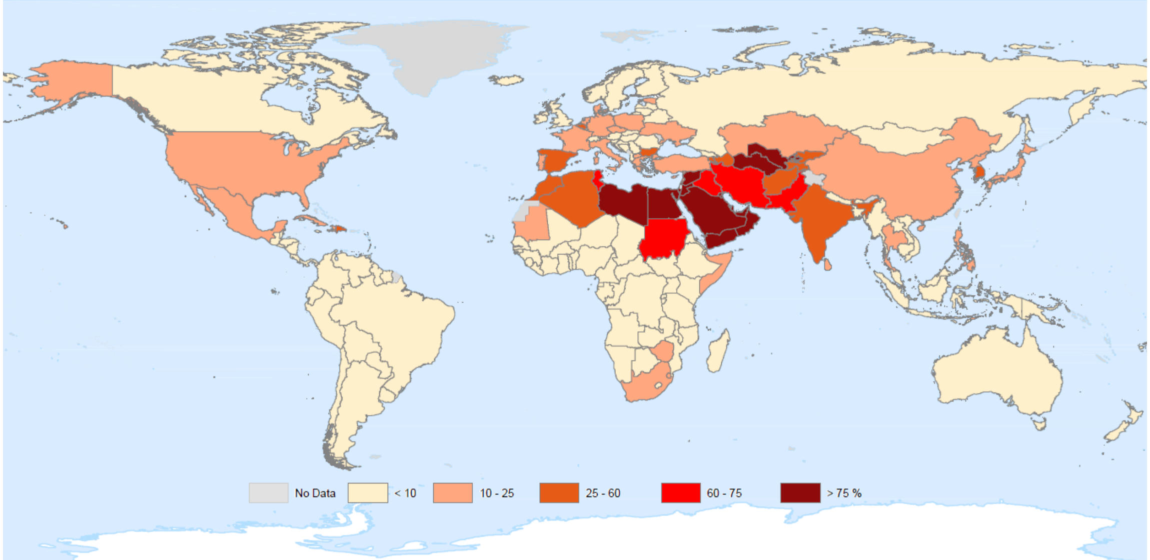

Figure 1. Percentage of withdrawal of renewable water resource in 2015

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The map shows clearly that the regions in which water issues presently are and will appear in the future more severe are North-Africa, Arabic peninsula, Middle East, and India in which there's a higher population density. In these regions water withdrawal overcomes 60% of the total renewable resource. Despite sub-Saharan region appears not involved in this issue, the uncontrolled rapid urbanization happened between 1990 and 2012 have reduced the percentage of population that have a direct access to piped water. In this case the problem of fresh water access is rather an infrastructure issue then a resource deficiency.

Up to now, the alternatives to satisfy the increase of water demand are to dig deeper to access available water resources or exploit other innovative solutions such as the use of reclaimed water or the reverse water osmosis process for sea-water desalination, that appears as the most promising solution for that problem (UNESCO, 2015). The use of technologies for wastewater treatment and water desalination are research object of many scientific research (Youssef et al., 2016; Siddiqui et al., 2016; Chiavazzo et al., 2017). The typical solutions become economically feasible for large plants only. Moreover, they are quite energy intensive, being based on the use of fossil fuels and, causing a large carbon footprint of the produced fresh water. Further on, it appears evident that persons that lack the access to water will also likely lack the access to electricity or other fuels to power decentralized solutions. There are a lot of countries nevertheless in which both the distance from brackish or polluted water resources is an obstacle for these alternatives, arid areas of inner region of North-Africa and the Arabic peninsula commonly face this problem. The atmosphere, containing 12,900 km^3 of fresh water in the form of water vapor, could be an alternative to this situation and should be considered as a valid renewable source of fresh water. Just for comparison, liquid fresh water at the earth surface is about 110,000 km^3 and superficial rivers, which represent the first source for human use, 2,107 km^3 (El-Ghonemy, 2012).

2. Water extraction from atmosphere

The possibility to use ambient air as water source has been already studied and tested in different research activities (El-Ghonemy, 2012). There are two main valid options:

- Use a refrigeration cycle based on vapor compression heat pumps or absorption chillers, to cool the air under dew point and condense the moisture (Margini et al., 2015)
- Use sorption materials to subtract the water vapor contained in the atmosphere. Afterwards the material is regenerated and the water is condensed at ambient temperature (William et al., 2015)

The system proposed in this paper is based on the second approach, a thermodynamic cycle is investigated as a feasible and practical solution driven by solar renewable energy, and experimental tests are carried out to investigate relative potentialities.

A fundamental role in this cycle is played by the heat provided at low temperature, 50-80°C, that can be easily and economically produced by low temperature solar technologies: flat-plate or evacuated tube solar collectors. This way of producing heat has high compatibility with such regions that are characterized by arid climate conditions, in which the problem of water scarcity is frequently coupled with a huge amount of solar radiation. Furthermore, the low level of temperature of the heat supply opens the access to a huge amount of *"alternative"* heat sources, such as waste heat or thermal cascade from other technological processes.

The cycle alternates two different successive phases as shown in Figure 2:

- *Adsorption*. Water vapor capture from the atmospheric air exploiting adsorption material such as silica gel, Zeolite, addicted clay, etc…
- *Desorption*. Very hot and humid air stream production by the regeneration of the adsorption material providing heat to the system.

The hot and humid flux is then condensed in a dry cooler at the outdoor ambient temperature. To have significant production of water during condensation it's necessary to produce an air stream reaching a sufficient level of temperature and humidity so that the environment might be accepted as an effective condenser. This consideration has to deal with the physics behind adsorption/desorption of water vapor in the material. Humid air when exposed to adsorption or desorption transformations moves along an isenthalpic line. This means that variation of air moisture content is always linked to a variation of air temperature: during adsorption, moisture content reduces and air temperature increases; conversely, during desorption moisture content increases and air temperature reduces. For instance, if we want to have a condensing stream at the ambient temperature of 35°C, the saturation point corresponds to about 36.5 g kg^{-1} (point 3 in Figure 3). The only way to reach points on the saturation line above this reference point with an isenthalpic transformation is to have at the inlet of the desorption phase air at temperature around 50°C with the same moisture content (point 1). Anyhow, the moisture content at the saturation is very poor (point 2 iso-H) and just a reduced amount of water would be condensed (4-5 g/kg).

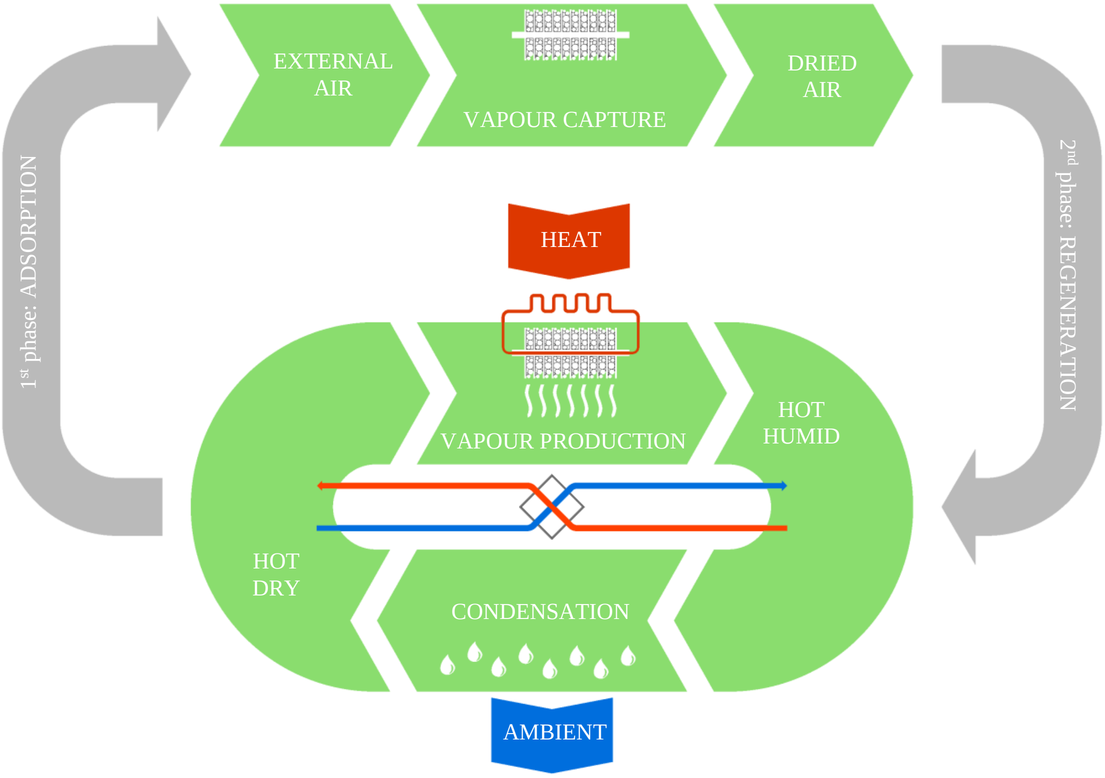

Figure 2. Conceptual scheme of the adsorption/desorption cycle

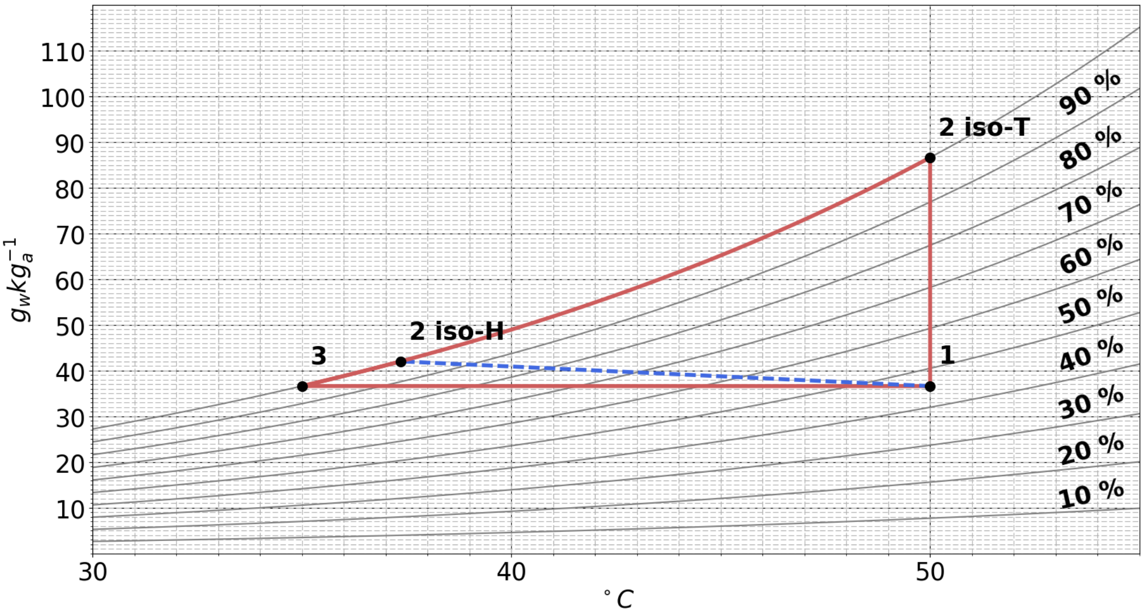

Figure 3. Comparison between a desorption with an isenthalpic (iso-H) or isothermal behavior (iso-T)

A different solution is when the sorption material follows a desorption transformation with an isothermal behavior

(2 iso-T). The specific humidity difference, starting from the same regeneration starting point (1), exceeds 40 g kg^{-1}, far more than the 5 g kg^{-1} given by the isenthalpic transformation. Obviously, this huge difference will require an equivalent amount of energy to allow the movement of water molecules from sorption material to the air. This amount of energy is slightly above the latent heat of water evaporation multiplied by moisture content difference. The point is that, to obtain the point 2 iso-T one has to supply an amount of heat equivalent to the latent heat, but always at the same temperature, 50°C. On the contrary, if point 2 iso-T had to be reached by an isenthalpic line the heat supply temperature would be above 70°C. This gives important advantages in terms of efficient utilization of solar thermal source at low temperature (flat plat or evacuated tubes), and limits the design problem only to the thermal requirement from the source.

To realize an isothermal transformation a system is required, that gives the possibility to exchange at the same time heat and mass. To do this, the sorption material such as Silica gel, Zeolite, etc. can be arranged in a finned heat exchanger (HX-ADS) (Finocchiaro et al., 2016; Simonetti et al., 2016). The heat to the adsorption heat exchanger is supplied by water circulation at 50-80°C, and a quasi-isothermal regeneration occurs. A fan circulates the air flow through the HX-ADS in a closed loop, thus permitting to continuously subtract water from the sorption material. The quasi-isothermal regeneration (line 1-2 iso T) is fundamental to obtain a hot and humid air stream from which water vapor can be easily condensed using ambient temperature in a dry cooler.

After this stage the air is cooled down by a double step thermal exchange: first by a heat recovery to reheat the regeneration stream and second by the condenser at the environment temperature. According to the thermodynamic cycle described in Figure 2 and Figure 3, around two liters of water can be collected from the treatment of an air volume of 100 m^3. In Table 1 different commercial solutions using vapor compression or absorption chillers are compared, in order to cool down the air to the dew point obtaining liquid water. Main differences of the proposed solution are the thermal supply at lower temperature, and lower specific consumption in terms of primary energy.

Table 1. Comparison of the proposed solution to existing commercial product and not.

	PROPOSED SOLUTION	AWA MODULE SEAS	WATER GEN	WATER FROM AIR	DESICCANT WHEEL	US 8584480
Technology	Adsorption material regeneration	Chiller (r134a)	Chiller (r134a)	Chiller (r134a)	Adsorption material regeneration	Absorption chiller (Li-Br)
Energy Supply	Heat	Electricity	Electricity	Electricity	Heat	Heat
Technology source	Solar thermal; waste heat; biomass	Fossil fuel; electricity power	Fossil fuel; electricity power	Fossil fuel; electricity power	thermal	Waste heat from diesel
Specific consumption	0,6 kWh_{th} lt^{-1}	0,6 kWh_{el} lt^{-1}	0,33 kWh_{el} lt^{-1}	0,33 kWh_{el} lt^{-1}	19 kWh_{th} lt^{-1}	-
Minimum supply temperature	55°C	-	-	-	80°C	100°C
Production in arid climate	+++	+	+	+	-	+
Use of renewables	+++	Indirect by RES	Indirect by RES	Indirect by RES	++	+
Use of waste heat	+++	None	None	None	++	++

3. Prototype

In the laboratory of the Energy Department (DENERG) of Politecnico di Torino a prototype has been assembled composed by and adsorption heat exchanger (Figure 4), and a condenser with a heat recovery system Figure 5. The adsorption system contains about 20.5 kg of silica gel grain with an average diameter of 3 mm. The heat is supplied to that system by a water circulation between 50-80 °C, produced by an electric resistance of 1.25 kW. The condenser is composed by an air to air heat recovery system and an air to water radiator which is used to condense the hot and humid stream, through cold water taken from water network, at around 20°C.

Integrated-Circuite temperature sensors LM35CAZ, with a precision of ± 0.2°C, monitor air and water temperature through the cycle. The RH sensor is a thermoset polymer capacitive type with on chip conditioning HIH4000-4 sensor monitors humidity at the inlet and outlet of the adsorption heat exchanger with a precision of ± 3.5%. The air flow is driven by a centrifugal fan, at variable velocity with a maximum power consumption of 43 W, and an air flow rate range 0-100 $m^3 h^{-1}$. The two parts, adsorption/desorption packed bed and the condenser, are connected by a flexible duct: the outlet of the adsorption heat exchanger with condenser's inlet, and the condenser's outlet with the adsorption stage's inlet.

Figure 4. Adsorption heat exchanger

Figure 5. Condenser and heat recovery system

4. Experimental Tests

The testing procedure and preliminary results of the prototype operation are here presented.

Each test, as explained in the concept of the cycle, is composed by two successive phases. First the outdoor air circulates at the maximum flow in the adsorption bed, until equilibrium with adsorption material is reached with the air inlet condition, and the material can be considered as "quasi-saturated". Due to the prototype design this phase takes tens of hours, during which only the air at the inlet and outlet are monitored, in terms of temperature and humidity. After that, hot water starts to circulate through the coil of the adsorption heat exchanger and heats up the material. When the desired temperature is reached, flexible ducts are connected to the condenser and the fan is turned on. The regeneration starts, and humidity and temperature at each step of the cycle and the inlet/outlet water temperature are monitored. Finally, condensation starts, and water droplets are collected in a recipient, Figure 6. At the end of each test the water is discharged and the total amount is finally weighted with a high precision scale.

Figure 7 shows data monitored during the adsorption phase. This part of the test had a duration of more than 18 hours, with an average air inlet temperature of 22 °C and an average inlet air humidity of 8 g kg^{-1}. The outlet air from the adsorption bed reached a maximum temperature of 37.5 °C after around two hours from the start of the test, showing as the combination of a very high amount of sorption mass (20.5 kg) and a low air flow rate (100 $m^3 h^{-1}$) leads to a huge inertia of the system. In this phase outlet air moisture content drops down to 1 g kg^{-1} at the beginning of the test. The adsorption phase is stopped when outlet moisture content is around the inlet value. Figure 8 and Figure 9 shows data monitored during the desorption phase, that have a duration of about 6.5 hours. This phase has been divided in 5 successive intervals in which, between each other there isn't air flow but only hot water circulation. These intervals are visible in the graphs by the unshaded band, in this way at each interval the desorption starts at higher temperature. Condensation temperature is between 15 and 20°C depending on the temperature of the water network. Air flow rate have changed from 50 to 100 $m^3 h^{-1}$ during the desorption phase. The moisture content of the air had a big variation in each interval from 100 to 30 $g kg^{-1}$.

In Figure 10 to Figure 14 the cycle on the psychrometric chart is depicted for each interval of the desorption phase. It can be noticed that:

- Maximum moisture content at the outlet of the bed reduces progressively in each interval as consequence of the reduction of water contained in the adsorption material (red points)
- Air in the condenser always reaches the saturation condition, and all points fall on the 100% line of relative humidity (pale blue points)
- The temperature difference between the outlet of the bed and the outlet of the heat recovery system increases, following the increase of the sensible thermal exchange (red and yellow points)
- There’s a big temperature difference between the inlet to the bed and the outlet of the heat recovery system caused by high thermal losses that occur in the path through the flexible duct that connect these two components. (blue points)

The total amount of water obtained from this test is equal to 2.318 kg. Starting from electrical power of the resistance (1.25 kW_{el}) and the total period of active desorption, 220 minutes, the thermal consumption is found to be 4.583 kWh_{th}. Then, the specific consumption results in 1.98 kWh_{th} lt^{-1}, that is 3.3 times the ideal value found through the thermodynamic analysis shown in Table 1. It has to be considered that numerous thermal losses occur in that system, the highest being in the duct between the condenser’s outlet and the sorption bed’s inlet, that can be estimated from the temperature difference between these two points, equal to 0,5 kWh lt^{-1}, or 25% of the total amount.

Another point is that the definition of the thermal specific consumption parameter in terms of total values, total thermal energy consumed and total water condensed, does not consider the transient behavior of the packed bed. In other terms, despite the thermal power provided to this system is always constant, the production of water decreases in time as the reduction of moisture content difference between inlet and outlet of the sorption bed. As a result of that, specific thermal consumption is not constant but an increasing function of the operating time. This behavior has been estimated in Figure 15, where positive difference of the air moisture content in the desorption phase is compared with a specific energy indicator, e_{th}, defined as follow:

$$e_{th} = \frac{P_{th}}{\dot{Q}_a * (X_{out} * \rho_{out} - X_{in} * \rho_{in})} = \left[\frac{Wh}{gr_{H_2O}}\right]$$

This function has two characteristic behaviors in time:

- *Continuous increase*. For each interval the increase is strictly correlated to the reduction of the outlet moisture content. This variation is very consistent such that at the end of each interval the final value is many times larger than the initial one.
- *Step behavior*. The reduction of internal moisture content of the sorption material amplifies the continuous increase between each interval. Instead the increase of the regeneration temperature between each interval shift down the initial value of the specific energy consumption. In this case the temperature and the duration of the hot water circulation period between each interval plays a fundamental role that is strictly related to the diffusive resistance of the water vapor in the micropore of the sorption material.

The correct management of heat in the regeneration phase has a large influence on the efficiency of the process, and thermal consumption can be reduced by an optimized control strategy.

Figure 6. Water droplets formation during condensation are collected in a basin.

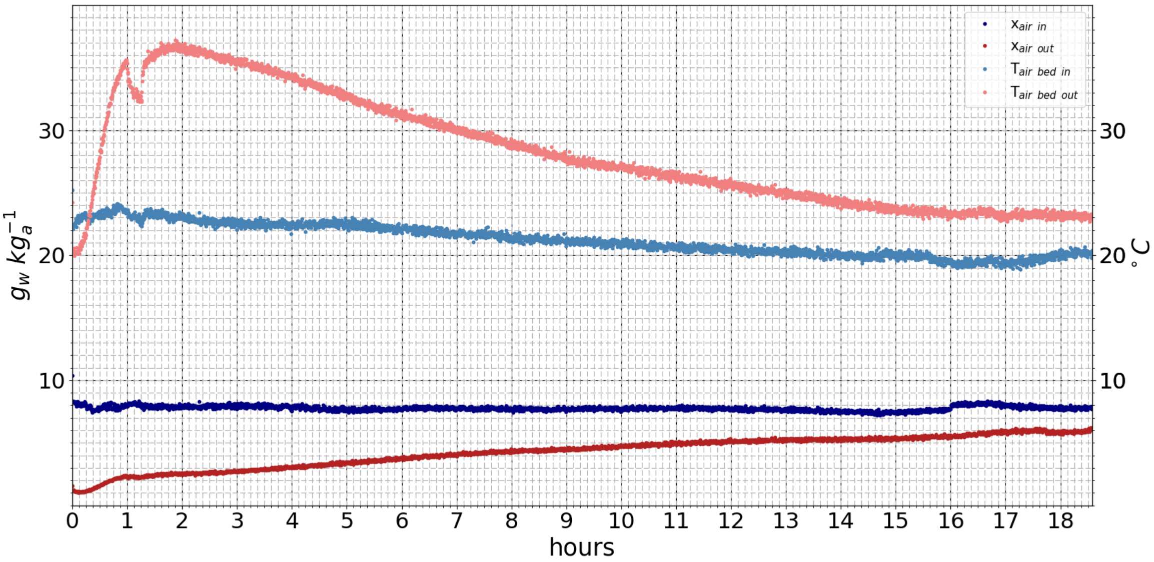

Figure 7. Air temperature and humidity profile during adsorption phase of the test

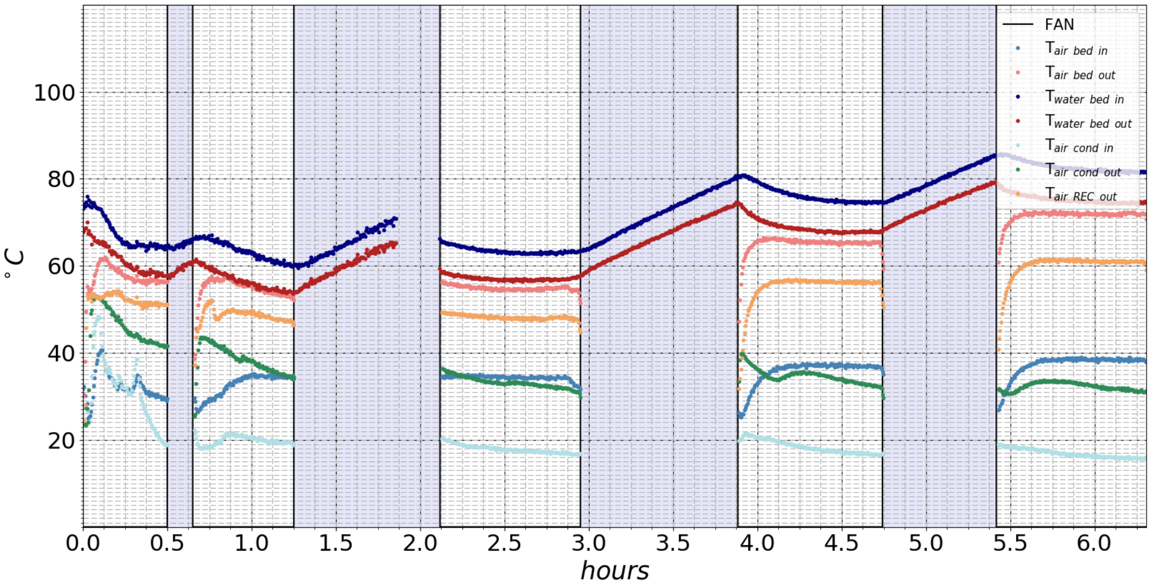

Figure 8. Air and water temperature profile during desorption phase of the test

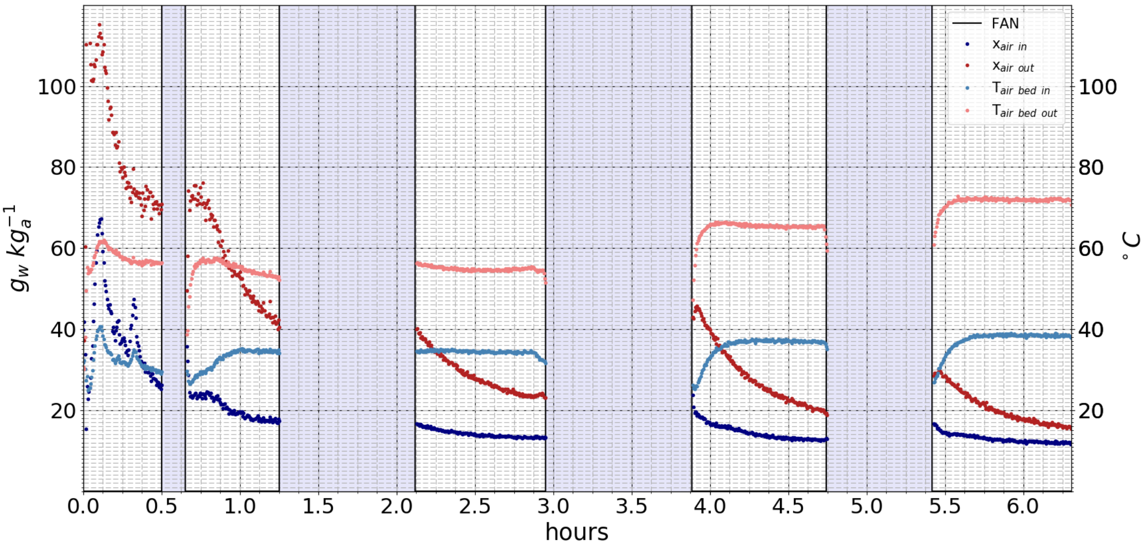

Figure 9. Air temperature and humidity profile during desorption phase of the test

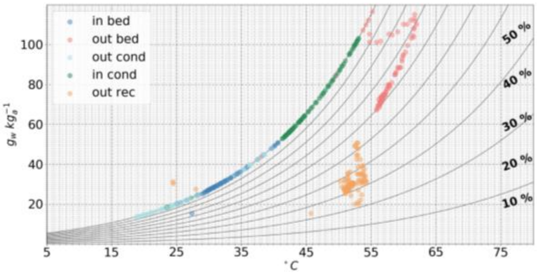

Figure 10. Cycle represented on psychrometric chart during the 1st part of the desorption

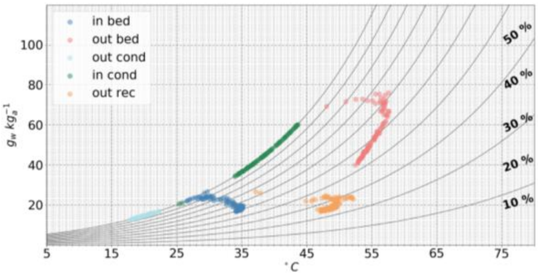

Figure 11. Cycle represented on psychrometric chart during the 2nd part of the desorption

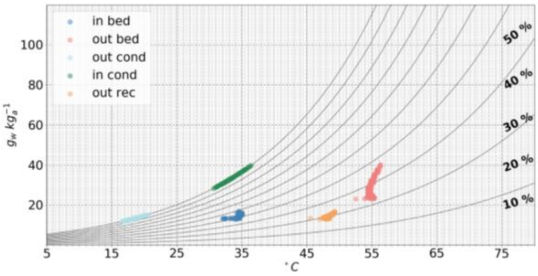

Figure 12. Cycle represented on psychrometric chart during the 3rd part of the desorption

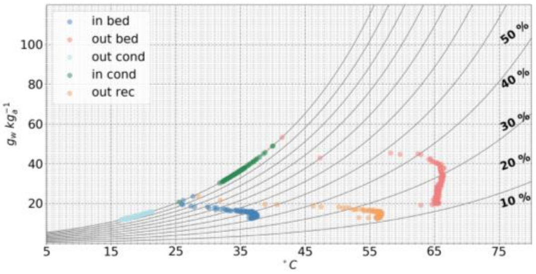

Figure 13. Cycle represented on psychrometric chart during the 4th part of the desorption

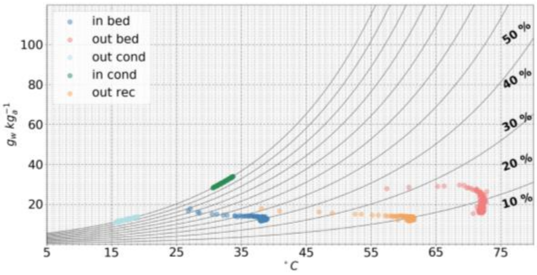

Figure 14. Cycle represented on psychrometric chart during the 4th part of the desorption

Table 2. Desorption interval

INTERVALS	Interval duration	Reg Temperature	Air Temperature
	min	°C	°C
1st	30	65	57
2nd	36	60	53
3nd	50	63	56
4th	49	74	65
5th	55	81	71

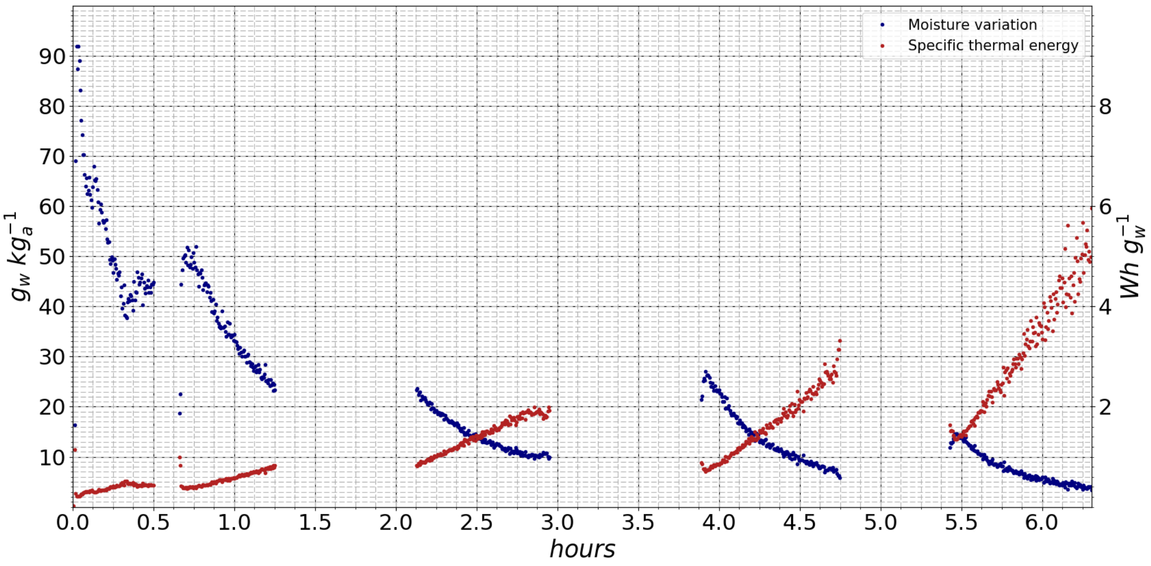

Figure 15. Evaluation of the specific thermal consumption of the desorption test (red), based on the variation of moisture content between inlet and outlet of the bed (blue).

5. Conclusion

The goal of this research is to demonstrate the feasibility of a system that catches the water vapor from air for many hours, such as a nocturnal period, and condenses this vapor using low temperature (50-80°C), solar heat. The prototype here presented has been tested in the laboratory of Energy Department (DENERG) of Politecnico di Torino. Preliminary results showed the capability to concentrate the water vapor contained in outdoor air for 18 of hours in the sorption material. Afterwards, with the use of heat under 80°C this vapor was released in about one fifth of the time to an air stream and condensed in order to obtain liquid water. A quantity of 2.318 lt of water has been obtained with an energy consumption of 4,625 kW_{th} of heat for an active period of operation around 3,7 hours.

Efficiency and performances of the process can be increased, and different strategies will be implemented to increase the efficiency of the system and reach values close to the theoretical value of 0,6 $kW_{th}\ lt^{-1}$, such as: the increase of ducts insulation; reduction of the length of air ducts; improvement of the regeneration strategy. New tests will be carried out with different outdoor temperatures and moisture contents, in order to simulate different climatic conditions such as in hot humid and arid countries. Also, the condensation temperature will be varied in a range of temperature between 15-35°C. Chemical test on water will be carried out in order to understand the best treatment needed to transform it in potable water.

Finally, we may say that the experiment has validated the concept on which this type of machine is based, and has shown an encouraging prospective.

6. References

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Table 3. Symbols legend

Quantity	Symbol	Unit
Temperature	T	°C
Moisture content	X	$\mathrm{g_w\ kg_a^{-1}}$_
Relative humidity	RH	%
Enthalpy	h	$\mathrm{kJ\ kg^{-1}}$
Volume	V	$\mathrm{m^3}$, lt
Energy	E	kWh
Specific energy	e	$\mathrm{Wh\ g_w^{-1}}$
Power	P	kW
Air flow rate	$\dot{Q}$	$\mathrm{m^3\ h^{-1}}$
Density	ρ	$\mathrm{kg\ m^{-3}}$
Time	t	h
Mass	M	kg

Table 4. Subscripts legend

Quantity	Symbol
Isoenthalpic	*iso-H*
Isotherm	*iso-T*
Water	*w*
Air	*a*
Thermal	*th*
Electrical	*el*
Inlet	*in*
Outlet	*out*
Condenser	*cond*
Heat recovery	*REC*
Adsorption packed bed	*bed*
Adsorption	*ADS*
Regeneration	*REG*