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A hybrid passive cooling wall system: concept and laboratory testing results

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Abstract

The research unit associated to the Laboratory Systems for Technology Innovation (LaSTIn) of the Department of Architecture and Design as well as the Department of Energy, Polytechnic University of Turin, has investigated the possibility of producing a modular wall system for hybrid/natural passive cooling. This system uses pressure differences typical of natural air movements and it is conceived as a mean to reach a quasi-zero-energy building as foreseen by Dir. 2010/31/EU by 2020 for new constructions. In addition, it realises a high level of technological and architectural integration in building constructions.

The research focuses on passive and solar cooling techniques and studies the following possible systems, designed and tested separately in laboratory: a) latent heat adsorption cells including silica gel and zeolites for controlling the specific air humidity content, with heat regeneration by a vacuum water solar collectors system; b) a low-pressure heat exchanger, with crossing flows through ducts of rectangular section, to recover sensible heat/cold from return air; c) a passive evaporative cooling element.

This paper present the design concept of the wall system as well as a first series of results from laboratory testing regarding the latent heat absorption component.

Peer-review under responsibility of the CENTRO CONGRESSI INTERNAZIONALE SRL.

Keywords: dynamic simulation; hourly typical meteorological years; building simulations; energy performance

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1. Introduction

The trend of end-use electricity consumption in Italy for the next decade foresees the largest relative increase in the tertiary sector followed by the domestic sector, both related to building use and operation (Table 1).

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Table 1. Trend of end-use electricity consumption in Italy 2012-2023 by sectors [1].

Sector	2012	2018	2023	*2012-2023*
	(TWh)	*(TWh)*	*(TWh)*	*a.i.r. %*
Agriculture	5.9	6.0	6.1	0.2
Industry	130.8	126.9	134.9	0.3
Tertiary	*101.0*	*113.1*	*133.7*	*2.6*
Domestic	*69.5*	*70.6*	*75.3*	*0.7*
Total end-use	307.2	316.6	350.0	1.2
Grid Lossess	21.0	19.2	19.9	-0.5
Total	328.2	335.8	370.0	1.1

Two synergic actions contribute to this trend: global warming due to green-gas emissions and enhancing of summer indoor thermal comfort conditions as shown by the increase of air-conditioners stock [2].

A policy implementing energy efficiency could reduce the predicted increments at 2023 from 2.6 % to 1.5 % for the tertiary sector and from 0.7 to 0.2 for the domestic sector [2]. Within this framework, a wide-spread application of passive and hybrid cooling systems represents an effective strategy.

2. Passive cooling systems: concept and classification

Table 2. Classification of passive/hybrid cooling systems

Type of technique	Thermal Sync	Heat transfer mechanism	Fluid circulation driving force		Integration to building structure, envelop, and services
			Air	*Water*	
Night Ventilative Cooling (NVC)	Ambient AIR *($T_a < T_{setpoint}$)*	conduction convection radiation	wind thermal gradient	-	massive walls and slabs air-temperature-driven automatic openings
Earth-to-fluid Heat Exchangers (EHX)	GROUND *(depth > 2.5m)*	conduction convection	fan	pump	all-air ventilation system *(dedicated Air Handling Unit)*
Passive Downdraught Evaporative Cooling (PDEC)	WATER *(nebulized)*	convection latent heat	downdraught fan	-	indoor large spaces
Indirect Evaporative Cooling (IEC)	WATER *(nebulized)*	conduction convection latent heat	downdraught fan	-	all-air ventilation system water-to-air duct cooling system
Indirect Radiative Cooling (IRC)	NIGHT SKY	radiation	thermal gradient fan	pump	radiative roof cover glassless solar collectors
Adsorption Desiccant Cooling (ADC)	Adsorption materials	latent heat	thermal gradient fan	pump	adsorption cells regenerated by hot water or air (solar energy source)
Low-pressure Heat Exchange (LHX)	Indoor extract AIR	convection	thermal gradient fan		replacement of high-pressure heat-recovery systems

Passive and hybrid cooling systems are based on the use on natural thermal syncs as an alternative to mechanical heat-transfer processes. The difference between “passive” and “hybrid” is only due to the type of driving force for fluid circulation: natural in the former, mechanical in the latter. Depending of the type of thermal sync, various types of passive cooling techniques can be applied as shown in Table 2.

The wall system here described is a hybrid cooling system combining NVC, IEC, ADC, and LHX types of technique.

3. Hybrid passive cooling wall system

3.1. General concept and functions

The research on hybrid passive wall systems (HPW) tests the following heat transfer mechanisms: open-circuit de-humidification by adsorption materials regenerated through solar collectors; evaporative cooling, either direct or indirect; low-pressure heat-cold recovery. Thermal fluid for indoor comfort is air, while secondary fluids are water for evaporative cooling, and either water or air for latent adsorption heat transfer. Fluids circulation can be both/either natural, through downdraught and stack effect, and/or mechanical through fan or pump.

Its main innovative feature is the possibility of drastically reducing (in the case of forced fluid circulation), or even zeroing (in the case of natural fluid circulation), the electricity consumption and environmental impacts related to conventional vapour-compression AC systems. This is realised through the synergic actions of adsorption de-humidification, evaporative cooling, and a low-pressure heat exchanger aimed at obtaining performance close to current air-to-air heat-recovery systems but with a low-pressure airflow approaching natural airflow characteristics.

Another important innovative feature of HPW is its integration to building envelopes as a wall module pre-fabricated system. It was designed and built as a prototype within the combined programmes of two research projects: PR.I.M.E3 (PRocedure for Innovative Modules Energy Efficient and Eco-compatible), and VENTISOL.

This prototype was tested in the LaSTIn (Laboratory "Systems for Technology Innovation"), a Laboratory realised at Politecnico di Torino by DAD (Dept. of Architecture and Design) with the collaboration of DENERG (Dept. of Energy). Figure 1 shows a wall's component tested in the lab.

The industrialisation of this prototype and its application to demonstration buildings in various European locations and climate zones is foreseen within an International project submitted for funding to a 2015 call of Horizon 2020 EU Programme.

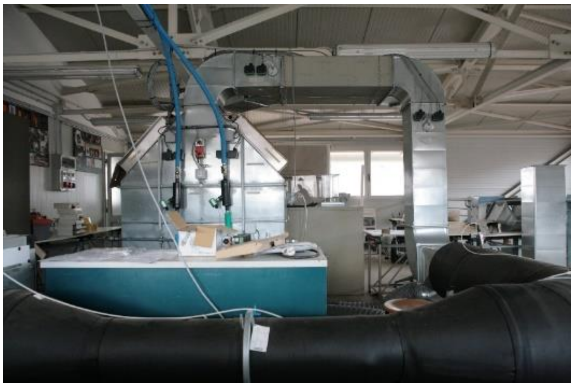

Fig. 1. A view of a wall's component tested in LaSTIn.

3.2. The testing laboratory

The testing facility is composed by a two ways airflow test circuit, a set of calibrated instrument and a numbers of active control on dampers and valves. The system is controlled by the text interface of a personal computer and implemented with a graphic user interface.

The main installed parts of hardware are the following:

- 2 Air Handling Units with a variable airflow rate in the range 300-1500 m^3/h, provided with electrical heating coil, humidification section, calibrated flanges;

- 10 m^2 of vacuum tube solar thermal system, with 1000l water storage.

The set of calibrated instruments measure the following parameters:

- differential pressure (range 0-20Pa, sensitivity 0.2Pa);
- temperature (range 0-100°C, sensitivity 0.3°C);
- relative humidity (range 0-100%, precision 4%).

The AHUs were used both in direct connection with the adsorption module, in order to test the module under mechanically driven ventilation, and in an indirect way, through an open plenum, inserted at the module intake vent. By using the plenum, open at the topside, the module was supplied with air at the desired thermodynamic condition, but at a zero pressure gauge, thus simulating natural ventilation conditions.

3.3. The humidity adsorption module

The adsorption module is a modular unit that adsorbs air humidity by means of a solid sorbent bed. Two different options were tested in laboratory, using both free running and mechanically driven airflow. The first option is a water/air coil, filled with silica gel spheres, the second model is an identical coil coated with a SAPO-33 zeolite layer.

Table 3. Coil dimensions.

Dimension	Value
Length	*600 (mm)*
Width	*480 (mm)*
Depth	*150 (mm)*
Fin Spacing	*8 (mm)*
Surface	*6.40 (m2)*

The two coils are connected to a water loop, supplied with hot water by the solar thermal system. The regeneration of the adsorbent bed is performed by air natural convection. Hot water circulates in the coils and air vent are opened, in order to allow a free airflow.

3.3.1. Silica gel module

The silica gel module was realised by filling the gap of one plate fin coil with silica gel spheres having a diameter of 3 mm. The vacuum ratio (ratio of vacuum volume to total volume) is 58%.

Dimensions of the coil are shown in table 3.

Silica gel module was designed to work for low pressure mechanical ventilation and is not considered for full natural ventilation application, because of a higher pressure loss. The regeneration and adsorption phases were performed under the assistance of the AHU net pressure head, with a pressure drop in the order of 15-20 Pa.

3.3.2. Zeolite module

A second coil was coated with a 1.5 mm-depth zeolite layer. The zeolite used is SAPO 34, whose linear formula is $(SiO_2)x(Al_2O_3)y(P_2O_5)z$. SAPO 34 is a micro pore zeolite, with a regeneration temperature sufficiently low as to be considered for solar thermal applications.

An advantage of this configuration, with respect to the silica gel one, is that the fin space is only partly occupied allowing for a fairly high free flow for natural ventilation application.

3.4. Results and comments

3.4.1. The results of an adsorption-desorption test on the silica gel module are reported in the diagram of Fig. 2a. Water supply and return temperature, and inflow and outflow air temperature, are plot as a function of time. Water temperature are only reported when the water loop in open, i.e., when the regeneration is performed. The two regenerations plotted are at different temperature levels, due to cooling of the solar thermal storage.

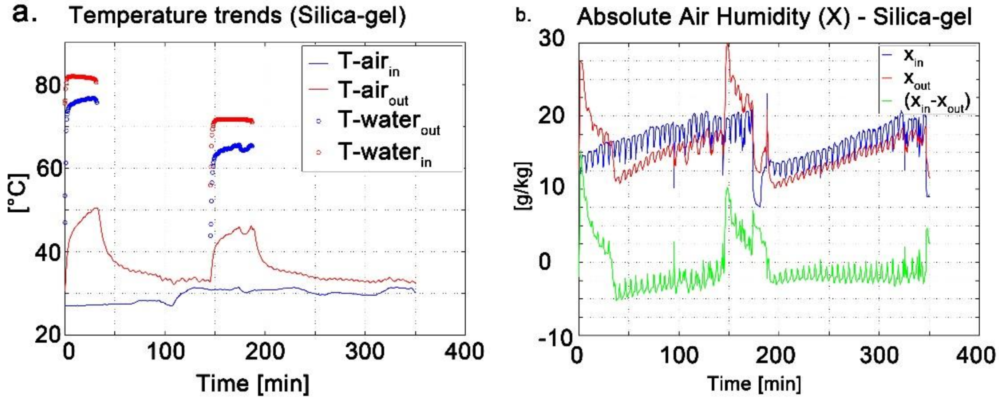

Fig. 2. Monitored temperature (a) and absolute air humidity (b) values during three adsorption/desorption cycles of the of the silica-gel coil.

In Fig. 2 (b) the absolute humidity of inflow and outflow air is plotted as a function of time, starting at the same time as in Fig. 2(a). The higher regeneration temperature of the first event produced a more complete desorption. This can be noted considering that the following adsorption, lasting from min. 40 to min.145, took place at a higher rate, in comparison with the next one, plotted from min. 190 on.

Fig. 3 reports the monitored absolute humidity and temperature values during three adsorption/desorption cycles of the zeolite-coated coil. As in the case of silica gel, it can be noted that the second cycle developed a worst adsorption phase, suggesting that the second regeneration was not as effective as the first one. This can be explained, again, by the lower temperature of supply water due to progressive cooling of the storage.

The two adsorption stages performed in a similar way. The average regeneration time was in the order of 30-40 min. Nonetheless, when the temperatures of supply hot water reached values below 75°C, the regeneration of both coils, the one filled with silica gel spheres and the one with SAPO 34 coating, produced a less effective adsorption phase. For these materials, a regeneration temperature higher than 75°C needs to be considered. The zeolite-coated coil demonstrated the possibility of regenerating the sorbent bed under free convective airflow, while silica gel needed a mechanical system integration.

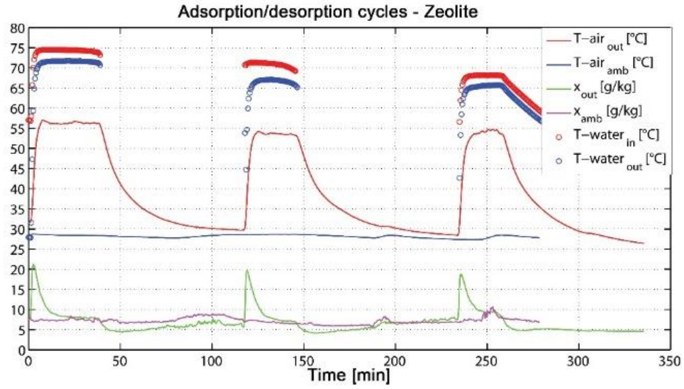

Fig. 3. Monitored absolute air humidity and temperature values during three adsorption/desorption cycles of the zeolite-coated coil.

4. Building integration

The hybrid passive cooling system was conceived for being embedded in a modular element to be mounted on an external wall as shown in Fig. 4. In this figure, the wall system is completed by two tilted elements on roof: an air solar collector working as a solar chimney to exhaust air naturally by stack effect; and a solar water collector to regenerate adsorption materials in the latent heat transfer module.

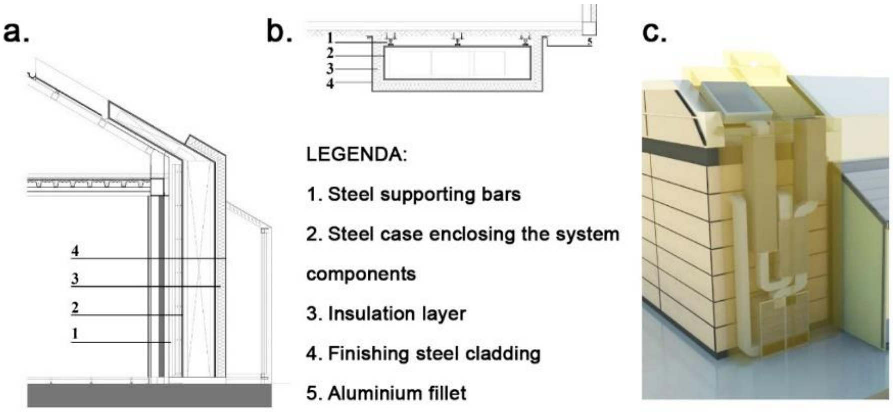

Fig. 4. Wall system integrated in a building: (a) vertical section; (b) horizontal section; (c) transparent view of the system components.

5. Conclusion

The hybrid passive cooling wall system here presented and, in particular, its adsorption latent heat exchange module, showed promising performance results at a laboratory testing level. Pending a patent process, the actual effectiveness of this system as a real alternative to conventional air conditioning systems needs to be demonstrated through a wide application on real buildings and related monitoring campaign. This was included in a proposal for funding submitted to a 2015 call in the LEIT (Leadership in enabling and industrial technologies) thematic area of the EU Horizon 2020 Programme.

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