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The Potential of Thermo-Active Building Systems (TABS) in Southern Europe: a Simulation Study

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Abstract

Thermo-Active Building Systems (TABS) represent a promising option for building conditioning, being well-spread in Northern and Central regions of Europe for dominant heating operation, but having a much slower penetration in warmer Southern climatic areas. In this context, the present work aims to evaluate the potential and main implications of such climatic differences on the energy and comfort performance of TABS. Their integrated operation with different cold water generation alternatives and control strategies is considered.

Results derived from the whole simulation work developed in TRNSYS 17 reveal important limitations for TABS cooling associated to humidity control issues in the hottest and most humid Mediterranean areas (e.g. Valencia). Nevertheless, other southern locations in the continental climate with quite hot and dry summer conditions (e.g. Madrid) show satisfactory results.

Moreover, this work estimates the potential of integrating hydraulic free-cooling provided by a cooling tower, and proves the interest of simple regulation strategies for TABS operation; such as the feedback control of the system's surface temperature or the alternation of night-active and day-passive periods.

Finally, the consideration of an adaptive thermal comfort model also demonstrates the opening of many more possibilities for TABS than those associated to situations in which Fanger's comfort criteria are assumed. This generates an interesting debate on the suitability of adaptive models for TABS buildings operated in passive regimes and its implications on a more energy-efficient exploitation of such systems in warmer climates of Southern Europe.

Keywords - radiant cooling; TABS; TRNSYS simulation; adaptive comfort

1. Introduction

Thermo-Active Building Systems (TABS) consist of water pipes embedded into the building concrete structure in order to provide radiant heating and cooling to the indoor environment from the floor and/or ceiling surfaces. These systems use the building mass as an energy storage whose dynamic thermal behavior is exploited to reduce the energy demand and improve the efficiency on the use of energy [1].

TABS can be nowadays considered as a well-spread technology in Northern and Central regions of Europe for dominant heating operation, but they have had a much slower penetration in Southern climatic regions [2, 3].

To this regard, the main current challenges associated to the development of radiant conditioning systems (in particular, TABS) focus on the possibility for extending their application to climatic regions with important cooling needs, the derivation and optimization of adequate control strategies [4,5], as well as the integration with sustainable generation alternatives providing low energy consumption [3, 6].

These tasks can be addressed through energy simulation, which constitutes a fundamental research tool capable of providing trustworthy comparisons and estimations on the behavior of conditioning solutions whose full-scale demonstration can be difficult in the early stages of development.

So, this work deals with the aforementioned aspects by setting out and developing a comprehensive simulation study that analyzes the energy and thermal comfort performance of TABS in different European climatic areas.

2. Methodology

The scope of the simulation study covers the analysis of four different aspects, as it is shown in Table 1. The main purpose focuses on the implications on TABS performance of the climatic differences between Central and Northern Europe and warmer southern regions. However, the influence of different cold water generation systems, control strategies and thermal comfort criteria, is also analyzed. More detailed considerations on these aspects are commented in the following sections.

Moreover, there is a general common framework within which all the simulation runs were performed. It comprises the following points:

- TRNSYS 17 software [7] was used to simulate the performance of each case study for the most demanding cooling period of the year (April to September) with a 1-hour timestep.
- Fig.1 shows the target virtual office building. It was thought according to a reasoned passive design that limits solar gains in summer and favors solar natural heating in winter. Besides, each floor consists of three different thermal zones (North, South and Interior) of similar extension. More information about the building constructive and geometrical features can be found in [8]
- Typical office schedules as well as a medium-load profile for the internal gains were set (maximum occupancy of 10 people/m^2, equipment loads of 140 W/person and lighting loads of 10 W/m^2).
- The minimum ventilation air flow rate was selected according to the Spanish standards [9] for office buildings: 45 m^3/(h·person). In order to

limit indoor RH (relative humidity) values, when needed, up to 90 $m^3/(h \cdot person)$ were used.

Table 1. Scope of the simulation study

		Thermal comfort models							
		Fanger ISO7730			Adapt. EN15251				
		Continuous	Night	Feedback	Continuous	Night	Feedback		
Climatic locations*	ZUR							AC	Cold water generation**
								CT	
								CT + WC	
	MAD							AC	
								CT	
								CT + WC	
	VAL							AC	
								CT	
								CT + WC	
		Operation strategies							

* ZUR: Zurich; MAD: Madrid; VAL: Valencia

** AC: air-cooled chiller; WC: water-cooled chiller; CT: cooling tower

NOTE: Colours correspond to different simulation studies: red: Study_1 / blue-lined: Study_2 (see section 3)

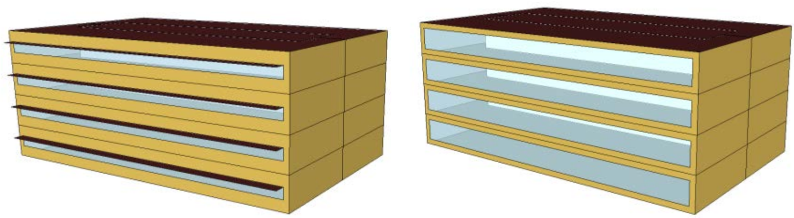

Fig 1. General view of the South (left) and North (right) façades in the virtual office building addressed on this simulation study.

- A reasonable TABS constructive design according to practical expertise and previous theoretical analyses shown in [8] was chosen for all the simulation case studies. Design parameters are specified in Table 2.

Table 2. Constructive design parameters of the TAB system.

TABS design parameters	Values	Units
Slab thickness, d	30	cm
Pipe external diameter, d_r	20	mm
Pipe thickness, δ	2	mm
Pipe spacing, d_x	15	cm
Pipe thermal conductivity, λ	0.35	$W\cdot m^{-1}\cdot K^{-1}$

- TABS water mass flow rate was set to 10 $kg/(h\cdot m^2)$ whenever the corresponding zone valve was open.
- Energy consumption from auxiliary equipment was determined on the basis of reference values derived from literature [10] and manufacturer data.

2.1. Climatic locations

In climate and environmental sciences, climatic conditions of particular locations are often classified according to the 'Köppen-Geiger' approach [11]. Nevertheless, more specific works have tried to develop other classifications accounting for particular factors that affect HVAC system performance [12]. Following a similar idea, in [8], 22 different locations along Europe were analyzed on the basis of their cooling and dehumidification needs associated to the Meteonorm climatic data. The three different classes proposed there, were used in the present work to evaluate the climatic differences on TABS performance.

Therefore, Zurich, representing conditions with low cooling and dehumidification needs normally found in Central and Northern Europe, was compared with two locations in Spain (Madrid and Valencia). They represent warmer climates in Southern Europe where TABS are sparsely deployed. Nevertheless, there still are some relevant differences between these two classes related to the cooling needs and the humidity conditions. Then, results are also expected to be sensitive to such differences.

2.2. Cold Water Generation Systems

Three different alternatives were considered, namely conventional air-cooled chiller, cooling tower (water side free-cooling) and a combined solution consisting of a cooling tower supported by a water-cooled chiller when needed (see Fig 2.).

Simulations accounted for the capacity and performance maps of particular commercial chillers that were conveniently sized for each case. Moreover, the cooling tower was characterized by a proper correlation to determine the available Number of Transfer Units (NTU). Particularly, (1) was taken from the studies of Costelloe and Finn [13] on the behavior of a low-approach cooling tower especially designed for heat rejection at moderate temperatures in radiant cooling applications. L and G (both in kg/s) represent the water and air mass flow rates into the tower respectively, K is the total (heat and mass) transfer coefficient ($kg \cdot s^{-1} \cdot m^{-2}$) and a·V accounts for the total heat transfer area (m^2)

$$NTU_{available} = \frac{K \cdot a \cdot V}{L} = C \cdot \left(\frac{L}{G}\right)^{n} = 1.3 \cdot \left(\frac{L}{G}\right)^{-0.77} \qquad (1)$$

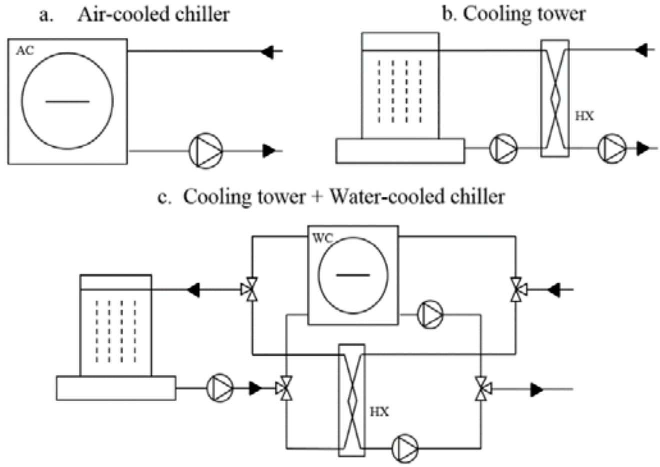

Fig 2. Sketch view of the three considered cold water generation systems.

2.3. Control Strategies

Although several studies on more advanced control concepts for TABS can be found in literature [4, 14, 15, 16], this work aims at evaluating simple strategies in order to prove their applicability and potential performance in a wide range of situations.

A simple cost function accounting for a balance between energy consumption and comfort requirements was used to perform the optimization of a constant water supply temperature. Then, this temperature was combined with three simple pump operation patterns which are briefly described next.

The 'Continuous' mode consists of uninterrupted water supply from 21.00h on Sunday to 20.00h on Friday. Weekends are 'OFF' periods in all the proposed concepts.

The 'Night' mode uses a 24h duty cycle with a 0.5 'ON'-fraction during the night period. This way the slabs cool down during 12 hours at night (charge), and increase its temperature when they absorb the daytime heat loads (discharge).

Finally, the third simple strategy consists of an 'on/off' control which receives 'feedback' information from an observed continuous variable that represents the state of the thermal zone or the radiant emitter. Considering previous work of Sourbron and Helsen [5], the TABS surface temperature was selected as the observed variable.

2.4. Thermal Comfort Models

Thermal comfort conditions in each simulation case study were evaluated on the basis of two of the most widespread models: the heat balance approach derived from Fanger's studies [17], and the adaptive model [18] implemented into the European standard EN15251 [19].

3. Results and Discussion

Results derived from the whole simulation work, which comprises more than 500 simulation runs in all, are divided into two different studies. Both of them consider all the climatic locations from Table 1 as well as both the thermal comfort models. 'Study 1' compares the different cold water generation options for continuous and night operation of TABS, while 'Study 2' analyses the behaviour of all the control strategies in combination with the 'cooling tower + WC chiller' generation case.

Total and auxiliary energy consumption (E_{tot} and E_{aux} respectively), as well as the cumulated periods exceeding the thermal comfort zone (Disc.) or the relative humidity limits (t_{RH}) are provided in this paper. Discomfort levels were quantified through the following indexes: PPDh (Predicted Percentage Dissatisfied-hours) for the Fanger's case and DDh (Discomfort degree-hours) for the adaptive case, defined as follows:

$$PPDh = \sum(PPD - 10)^{+} \tag{2}$$

$$DDh = \sum\left(T_{op} - T_{conf,up}\right)^{+} + \sum\left(T_{conf,low} - T_{op}\right)^{+} \tag{3}$$

Note that the + superscript indicates that only the hours with a positive value of the corresponding difference contribute to the addition calculation.

Moreover, results presented next correspond to the optimal values of the operational parameters (water supply temperature and surface temperature setpoints for the feedback control), that were found after the optimization methodology previously mentioned.

3.1. Analysis of cold water generation alternatives: Study 1

Table 3 shows relevant results derived from 'Study 1'. First, it should be noted that the total energy consumption is drastically reduced by the 'CT' cases. However, the cooling tower alone does not manage to provide comfortable conditions according to the Fanger's model (see orange cells in Table 3), which does not recommend its application under such conditions.

On the other hand, the intermediate solution (CT+WC) provides comfort results very similar to those from the conventional 'air-cooled' case study.

Also, although the cooling tower operation increases the auxiliary consumption, the 'CT-WC' total energy use is considerably lower.

Table 3. Results from the analysis of different cold water generation alternatives (Study 1)

			E_{tot}	Disc.	t_{RH}*	E_{aux}	E_{tot}	Disc.	t_{RH}*	E_{aux}
			kWh/m^2	PPDh	%	kWh/m^2	kWh/m^2	PPDh	%	kWh/m^2
CONTINUOUS	VAL	AC	24,8	59,5	43,6	2,9	22,4	0,4	8,5	2,9
		CT	7,0	24924,0	3,7	3,7	8,1	8,8	1,4	3,6
		CT+WC	21,9	60,5	43,6	4,2	17,2	0,4	8,5	4,2
	MAD	AC	22,7	47,6	3,1	2,9	20,7	6,4	0,3	2,9
		CT	7,4	2967,0	1,6	3,7	7,3	9,5	0,2	3,6
		CT+WC	16,8	47,4	3,1	4,3	12,3	6,5	0,2	4,3
	ZUR	AC	18,1	15,7	1,9	2,9	16,7	8,5	1,7	2,9
		CT	8,6	45,4	2,9	3,6	7,3	0,1	1,4	3,6
		CT+WC	11,5	15,6	1,9	4,2	9,6	1,7	1,7	4,3
NIGHT	VAL	AC	19,1	445,0	30,5	1,5	18,0	2,1	5,0	1,5
		CT	4,5	28991,0	3,1	2,2	5,6	33,6	0,9	2,2
		CT+WC	15,8	424,0	30,8	2,1	14,2	2,1	5,0	2,1
	MAD	AC	18,5	265,0	2,8	1,5	16,4	2,9	0,6	1,5
		CT	4,6	3666,0	2,3	2,2	4,6	9,2	0,1	2,2
		CT+WC	14,2	235,0	2,9	2,1	10,7	3,0	0,7	2,1
	ZUR	AC	16,0	73,8	2,7	1,5	14,3	5,9	1,0	1,5
		CT	4,7	189,0	4,9	2,2	4,6	0,0	1,1	2,2
		CT+WC	10,7	76,9	2,7	2,1	7,6	6,0	1,0	2,1
			FANGER'S MODEL				ADAPTIVE MODEL			

* t_{RH} is provided as a percentage of the overall occupation period during which the relative humidity value exceeds 70%.

Energy savings (when comparing 'CT+WC' and 'AC') range from 20% to 40% for relevant cases (see Fig.3). Note that when analysing TABS operation in southern regions, apart from energy and global thermal comfort there is another key aspect to be observed: latent load management or humidity comfort limits. In this study one can observe that climate conditions from Zurich or Madrid are not problematic in this sense. However, in relatively warm and humid climates (such as that of Valencia) ventilation cannot control the RH values, which constitutes an important handicap for TABS application (see green cells in Table 3).

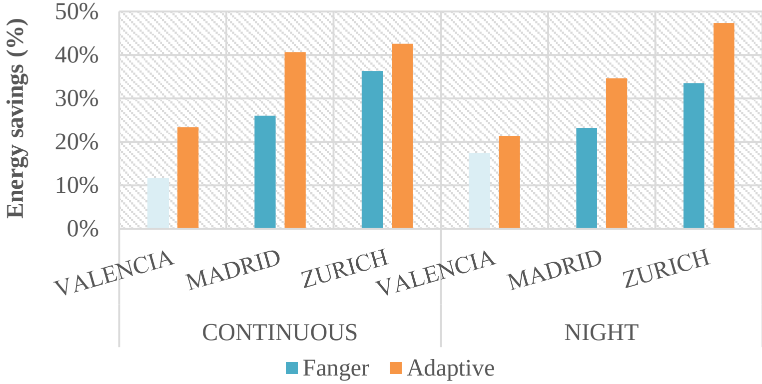

Fig 3. Energy savings obtained when comparing 'CT+WC' versus the conventional 'AC' alternative. (Fanger cases in Valencia are obviated since poor t_{RH} results make them irrelevant)

The consideration of the EN15251 adaptive model (with more flexible thermal comfort limits) allows some of the studied alternatives to provide satisfactory results and an interesting potential of application. Under these criteria, the 'CT' case provides now comfortable conditions with a reduction of the total energy use of more than 50% (see blue cells in Table 3).

3.2. Analysis of control strategies: Study 2

Table 4 shows relevant results derived from 'Study 2'. In view of them, the 'night' control strategy provides the lowest energy consumption for every case study (see orange cells in Table 4). However, discomfort indexes based on the Fanger's approach still are far from those desirable values. Then, under these criteria, 'feedback' operation results to be the most balanced option in terms of comfort and energy use (see green cells in Table 4).

Again, the flexibility of the adaptive model allows getting great performance with very simple control schemes (such as night operation) and the integration of water-side free-cooling.

This fact leads to a fundamental question that has not been yet deeply discussed by the research community: *Is the adaptive thermal comfort approach applicable to TABS buildings?* According to previous definitions from the adaptive theory [18], the strict answer should be 'No'. But, the particular application of this conditioning alternative involves a passive discharge process during occupation periods as well as an indoor environment strongly linked to the outdoor conditions, which may make the adaptive model application quite reasonable. Then, proving the satisfactory thermal perception of people under 'adaptive' environments in TABS buildings would be of great interest in the near future to justify the development of this sustainable integrated solution for building conditioning.

Table 4. Results from the analysis of different TABS control strategies (Study 2)

		E_{tot}	Disc.	t_{RH}	E_{aux}	E_{tot}	Disc.	t_{RH}	E_{aux}
		kWh/ m²	PPDh	%	kWh/ m²	kWh/ m²	PPDh	%	kWh/ m²
VAL	CONTINUOUS	21,9	60,5	43,6	4,2	17,2	0,4	8,5	4,2
	FEEDBACK	23,8	31,4	45,9	2,7	19,6	2,1	8,5	4,1
	NIGHT	15,8	424,0	30,8	2,1	14,2	2,1	5,0	2,1
MAD	CONTINUOUS	16,8	47,4	3,1	4,3	12,3	6,5	0,2	4,3
	FEEDBACK	19,2	2,4	8,5	2,5	13,3	6,8	0,2	4,2
	NIGHT	14,2	235,0	2,9	2,1	10,7	3,0	0,7	2,1
ZUR	CONTINUOUS	11,5	15,6	1,9	4,2	9,6	1,7	1,7	4,3
	FEEDBACK	12,1	0,5	3,6	2,9	10,8	9,7	0,9	4,1
	NIGHT	10,7	76,9	2,7	2,1	7,6	6,0	1,0	2,1
		FANGER'S MODEL				ADAPTIVE MODEL			

4. Conclusions

TRNSYS simulations have been used in this work to explore the potential for TABS application in warm Southern climatic regions of Europe. Results reveal important limitations for TABS cooling associated to humidity control issues in the hottest and most humid Mediterranean areas. However, other southern locations in the continental climate with quite hot and dry summer conditions, are not problematic and show very promising performance characteristics.

Moreover, this study proves the particular interest of integrating hydraulic free-cooling provided by a cooling tower as well as of simple regulation strategies for TABS operation.

Finally, the consideration of an adaptive thermal comfort model also demonstrates the opening of many more possibilities for TABS than those associated to situations in which Fanger's comfort criteria are assumed. This must lead to a fundamental discussion on the suitability of adaptive models for TABS buildings operated in passive regimes and its implications on a more energy-efficient exploitation of such systems in warmer climates of Southern Europe.

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