Experimental evaluation of a cooling radiant wall coupled to a ground heat exchanger

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Abstract

A building prototype was built in the experimental set-up located in Puigverd de Lleida (Spain) to study the energy performance of a radiant wall with ventilated facade cooled with a ground coupled heat-exchanger. The installed geothermal heat pump operates only as a ground coupled heat exchanger on cooling mode, thus providing free-cooling. In this case, only the circulation pumps consume power. The summer experimental campaign showed the energy savings potential and the peak load shifting ability of the system. On continuous operation and taking as reference a cubicle equipped with a conventional air-to-air heat pump, the radiant wall cooled with the ground coupled heat-exchanger achieved savings up to 54.17% and 82.08% at set-point temperatures of 24 ºC and 26 ºC, respectively. The thermal storage capacity of the system was studied in night charging test, when the cubicles were pre-cooled during night-time. During the day, the temperature raise caused by heat loads was small and the system kept the temperature inside comfort range despite it only operated overnight. However, the performance was very sensitive to set-point temperature. Free-cooling was limited by the temperatures in the boreholes, showing that with lower set-points the gradient between supply temperature and room temperature was small, and thus it required a higher water flow to achieve the necessary cooling power. Intermittent operation of the system according to different schedules also affected the radiant walls performance as they interacted with the thermal inertia of the system, which could even have a negative impact on energy use.

Keywords: TABS, Radiant Walls, Radiant Cooling, Ground Heat Exchanger

1 Introduction

There has been much concern on the energy consumption and greenhouse gases emissions on the last decades. According to the International Energy Agency (IEA) [1], buildings account for 32% of global energy use and almost 10% of total direct energy-related CO_2 emissions. Including electricity generation emissions (plus district heat), buildings are responsible for over 30% of total end-use energy-related CO_2 emissions. Buildings high energy consumption and high greenhouse gases emissions are global issues. Consequently, governments have developed legislations and regulations that tackle this problem. On this point, the European Directive 2010/31/EU stands that by 2020 [2] new buildings must consume "nearly zero" energy and those refurbished must be converted into very low energy buildings.

The use of thermally activated building systems (TABS) for radiant cooling has great potential in reducing building energy consumption and improving comfort conditions [3,4]. TABS are pipes or ducts embedded in the building surfaces or structures. These work as heat exchangers that provide heating and/or cooling to the rooms through activated surfaces that can be positioned on floors, ceilings, walls or in-floor slabs. These mainly exchange heat with the room in form of radiation. As TABS use the building large surfaces, the heat flux can be high even at low temperature gradients between the indoor air and the supply fluid. This point allows these radiant systems to operate with high temperature cooling and low temperature heating. As a result, the use of TABS improves chillers and boilers performance and makes feasible the use of low grade energy sources. In that sense, some research has been done to study the potential of free-cooling with TABS, often with ground coupled heat exchangers [5,6]. Furthermore, TABS store heat in the building components, characteristic that can be used for peak load shifting. Consequently, their operation can be shifted to low cost energy periods. Furthermore, peak load shifting may reinforce the use of environmental energy sources that are available for short periods of time, such as solar energy for heating or low outdoor air temperature for night-time pre-cooling [7].

As reflected in the literature about TABS, the development of numerical models has been a key point. They have been essential for TABS design studies and for their integration on building simulation packages. Simulations have been used for parametric studies [8,9], for control strategies development [10,11], and for studies of case buildings under different climatic conditions [12-14]. On the other hand, laboratory studies have been done for model validation and for evaluation of TABS heating and cooling capacity. Experiments of Tian et al. [15] showed that a 2D transient model obtained with Reaction Coefficient method had a 7% error compared to measurement. In contrast Ahmed et al. [16] studied experimentally the applicability of TABS on exposed roofs in tropical regions. On another point Song et al. studied the integration of dehumidification and radiant floor cooling [17]. Beyond the laboratory, experimentation has also involved monitoring of real building equipped with TABS. One example is the study of Kalz et al. [18], which involved the monitoring of multiple building. Also in this line, Meierhans [19] presented energy savings achieved in a building with ventilated core cooled with outdoor air during night-time. Furthermore, De Carli et al. [20] presented the first step of the optimization of the control for a building with TABS, whose results already showed the good comfort conditions achieved.

Most of the research on TABS considered horizontal configurations of the radiant surfaces (floor, ceiling, and in-floor) [7,21], while less research has been carried on vertical configurations (VTABS). On that topic, Zhu et al. [22] developed a 2D model Frequency Domain Finite Difference for pipe-embedded envelopes, which was used for a parametric study [23]. The model was improved with a genetic algorithm that defined the model parameters [24]. Later on, the Number of Transfer Units (NTU) method was added to the model, so that the temperature variation in the pipe direction could be taken in account [25]. In a similar line of research, Krzaczek and Kowalczuk [26] developed a Finite Elements model for Thermal Barriers (TB). This one was used for a parametric study of the TB coupled to a three level temperature geothermal system. As a follow up, a controller for TB based on Fuzzy Mixing Gain Scheduling (FMGS) was developed and simulated [27]. Finally, the components and structure of the TB were studied [28]. Bojic [29] also carried a simulation study, however, in this case EnergyPlus was used to compare radiant wall panels to conventional radiators. The results demonstrated that radiant walls had better synergy with the building insulation. On the experimental side, Venko et al. [30] made a laboratory study on the activation length of a VTABS under mixed convection conditions. Despite all these research, the literature found did not include experimental test of VTABS on real outdoor conditions, which is valuable information to evaluate the potential of such systems and validate simulation models with real data.

In this context, the present paper describes the experimentation in actual outdoor conditions in a house-like prototype scale. The cubicles built allowed for a comparative study of buildings with equivalent envelopes but using different HVAC systems, in that case a radiant wall coupled to a ground heat exchanger on a side and a conventional air-to-air heat pump on the other. Furthermore, the studied radiant wall was embedded into a heavy brick wall, which contrasts to previous studies were the system was embedded in concrete [22,26] or radiant wall panels were used [29,30].

The main objectives of the present paper are to study the energy savings potential of the system and to test different control strategies. To fulfil these objectives the research involved the construction and monitoring of a house-like cubicle, which was built with a radiant wall system embedded into a heavy weight brick and equipped with a ventilated facade. The radiant wall was coupled to a ground coupled heat-exchanger with two boreholes. This paper provides results from a summer experimental campaign.

2 Experimental set-up

The experimental set-up consisted of two house-like cubicles built in Puigverd de Lleida (Spain) experimental site, Figure 1 left. The internal size of the cubicles was 5.25x2.7x2.7 m. The roof was made using concrete pre-cast beams, 80 mm of polystyrene and 50 mm of concrete slab. The polystyrene was placed over the concrete and it was protected with a cement mortar layer with an inclination of 3%, a double asphalt membrane, and 50 mm of gravel. Details on wall and roof construction are shown on Figure 2.

The radiant wall cubicle was built with 185 mm wide alveolar bricks. Polyethylene pipes had 18 mm diameter and were embedded at 36 mm in grooves built on the internal surface of the wall with 150 mm spacing. On the outer part of the envelope there were 60 mm of expanded polystyrene insulation. A ventilated facade was built with 60 mm of air channel and openings at the bottom, middle and top sections of the wall as well as at the corners.

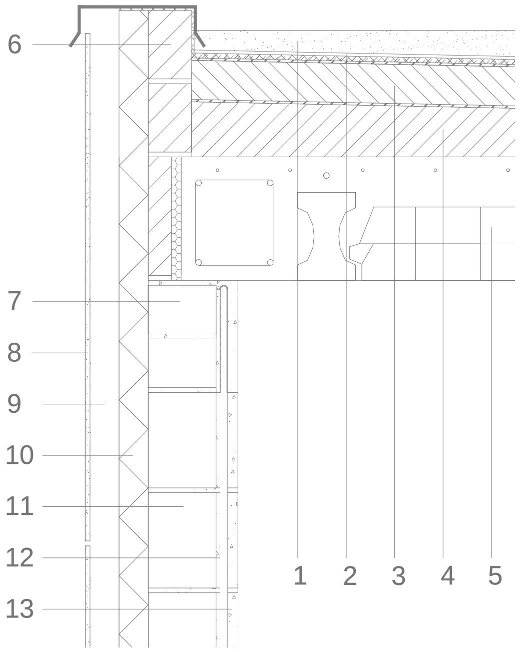
Five pipe loops of equivalent lengths were installed in the radiant walls: two on the South wall, one on the East, West and North walls. Flow and return pipes were placed on alternate grooves to maximise the temperature homogeneity on the wall surface, the configuration is shown on Figure 1 right. All the loops were connected to a common collector that distributed the cold water. The supply system was an ecoGEO B2 geothermal heat pump working in free-cooling mode. This device supplied cooling with a heat exchanger between the boreholes circuit and the radiant walls loops, thus it worked as a ground coupled heat-exchanger. The heat-pump compressor could only be used in the heating mode and consequently it was not used in the current study. Each of the two boreholes contained two U-pipes descending down to 20 m and 40 m, respectively. Table 1 summarizes the composition of the soil in the test-site.

Figure 1: Radiant Wall cubicle and reference cubicle (left) and detail on installation of embedded pipes (right)

Table 1: Test site soil characteristics

Depth (m)	Characteristics
0 – 5	Clay
5 – 7	Gravels (1st phreatic surface at 6 m)
7 – 8	Compressed dry fine sand
8 – 20	Very compacted clay, alternation of red and yellow layers
20 – 30	Gravels (2nd phreatic surface at 30 m)
30 – 40	Very compacted clay, alternation of red and yellow layers

A reference cubicle was built based on alveolar bricks constructive system. The objective was to compare the radiant wall cubicle performance against a conventional system. The comparability was ensured with the same thermal transmittance in steady state (U value) in both cubicle walls. Furthermore, the roof was built with the same system as the radiant cubicle. Therefore, the only differences between the cubicles were the heating and cooling system and the external ventilated facade. In that sense, the reference cubicle was equipped with Fujitsu ASHA07LCC air-to-air heat pump with a cooling capacity of 2.1 kW and a nominal COP of 4.47.



1 Gravel
2 Double asphaltic membrane
3 Polystyrene 8cm
4 Cement mortar, flat roof 3% sloped
5 Concrete precast beams + 5cm concrete slab
6 Hollow brick
7 Alveolar brick
8 Ventilated facade panel
9 Ventilated facade channel
10 Polystyrene 6cm
11 Alveolar brick
12 Polyethylene pipes
13 Groove for pipe filled with cement mortar

Figure 2: Wall and roof constructive details

The following parameters were measured and registered at 5 minutes interval:

- Internal surface temperature of walls, roof and floor (Pt-100 DIN B calibrated with a maximum error of ± 0.3 ºC).
- Borehole temperatures at 5, 10, 20, 30 and 40m (Sheathed Pt-100 DIN B calibrated with a maximum error of ± 0.3 ºC)
- Inside temperature and humidity (ELEKTRONIK EE21 with an accuracy of ± 2%).
- External temperature and humidity (ELEKTRONIK EE21 with an accuracy of ± 2%).
- Horizontal solar irradiance (Middleton Solar pyranometer SK08 ± 2 $W \cdot m^{-2}$).
- Electric energy consumption (Circutor MK-30-LCS-RS485)

3 Methodology

The experimental summer campaign was designed to study the performance of the cooling mode of the radiant wall coupled to a ground heat exchanger. The main goals were to analyse the influence of the set-point temperature, the operation schedule, and the wall thermal storage capacity. Also the influence of the ventilated facade on the cooling loads was studied. To test the performance of the radiant cubicle five experiments were carried out:

- Continuous operation: Cooling was operated to maintain a set-point temperature during the whole day. These experiments allowed studying the capacity of each system to maintain the set-point temperature and compare the electrical energy consumption in each cubicle. The tested set-point temperatures were 22 ºC, 24 ºC and 26 ºC, which were a set of temperatures that represent all the temperature ranges for comfort proposed in ISO 15251 [31] considering adaptable clothing from 0.5 and 1.0.
- Night-time charging: Cooling was operated from 0:00 to 8:00 at set-point 22 ºC. The systems pre-cooled the cubicles during night-time, when energy cost was lower. Furthermore the air-to-air heat pump on the reference cubicle worked during the more energy efficient conditions, when outdoor temperatures were lower. The experiment studied the thermal storage capacity of the cubicles, showing its capacity to maintain the indoor temperature along the day. Temperature raise along the day and time outside comfort conditions were studied in this experiment.
- Occupancy schedule operation: The cubicles were only cooled during defined occupancy schedules. Two different schedules were used: domestic schedule (from 17:00 to 8:00) and office schedule (from 8:00 to 13:00 and 14:00 to 17:00). The set-point temperature was 24 ºC during the occupancy schedule. These experiments provided knowledge about the response time of each system, the capacity to maintain the set-point temperature, and the electrical energy consumption in operation time when this was limited to an occupancy schedule.
- Free-floating: No active cooling was provided and the indoor temperatures of the cubicles were left to fluctuate influenced by the external conditions. This test shows the effect of the ventilated facade by comparing the profiles of the indoor temperatures

Operative temperatures were used to assess the thermal conditions inside the cubicles. This gave a better indicator of the radiant wall cubicle behaviour. Calculation of the operative temperatures was done according chapter 8 of ASHRAE Handbook Fundamentals [32]. It was calculated for a point at the centre of the cubicle at a height of 1 m, which corresponded to the actual placement of the sensors in the cubicles.

Note that all hour values are referred to local daylight saving time (DST), which in Spain corresponds to GMT+2 during summer.

4 Results and discussion

The experimental summer campaign started on June 2015 and lasted until the end of August 2015. No results were obtained during September because outdoor temperatures dropped significantly and no cooling loads were met at any set-point.

4.1 *Continuous operation test*

The test at 22 ºC was performed from June 13th to June 22nd. During this period, the ambient temperature ranged between 14 ºC and 28 ºC the first 4 days and between 14 ºC and 32 ºC the last 5 days. Moreover, the average daily accumulated solar radiation was 8.303 $kWh\cdot m^{-2}$. Weather conditions were warmer in the test at 24 ºC which was performed from June 24th to

July 1st. During the test, the outdoor minimum temperatures raised from 14 ºC to 18 ºC and the maximum temperatures raised from 30 ºC to 38 ºC with and average daily accumulated solar radiation of 9.133 $kWh \cdot m^{-2}$. Finally, the test at 26 ºC was performed from July 4th to July 10th in very warm conditions. During the first four days the ambient temperature ranged between 18 ºC to 42 ºC and between 16 ºC and 34 ºC in the last three days. During this last test the average daily accumulated solar radiation was 8.728 $kWh \cdot m^{-2}$.

On continuous operation test, the radiant wall coupled to ground heat exchanger was active for less time than the reference cubicle at all set-point temperatures, as shown in Figure 3. Furthermore, the reference cubicle required cooling during all the day except for some time at night. Additionally, the energy required for cooling increased during the day, matching the cooling demand. In that sense, the air-to-air heat pump worked at constant power and hence, the variation of energy consumed per hour reflects the fraction of time it actually operated. In contrast, the radiant wall operated for a single period each day, normally at the afternoon, when it cooled down the cubicle and stored energy. Despite this shorter operation time, the radiant wall cubicle had a small temperature fluctuation along the day. When actively cooling, the radiant wall worked at nearly constant electrical power consumption.

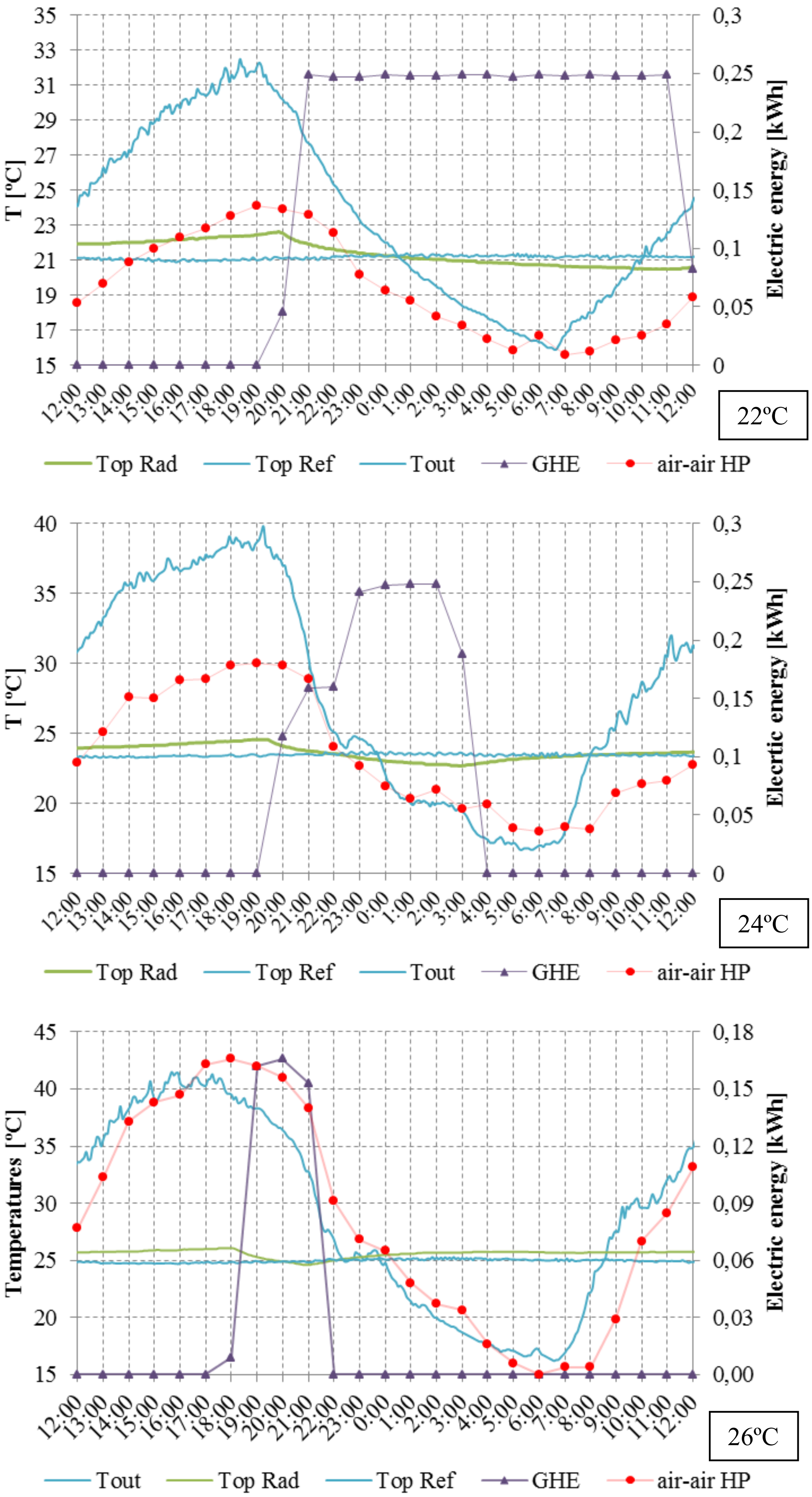


Figure 3: Operative temperature, outdoor temperature and hourly electrical energy consumed on representative days of continuous operation test at different set-points for the Ground Heat Exchanger (GHE) and the air-to-air Heat Pump (HP)

Table 2 Energy consumption and active time on continuous operation tests

	22 ºC		24 ºC		26 ºC	
	Energy (kWh)	Savings (%)	Energy (kWh)	Savings (%)	Energy (kWh)	Savings (%)
Radiant	11.79	-11.12	6.00	54.34	1.93	82.08
Reference	10.61		13.15		10.80	

Table 2 summarises the energy consumption of both cubicles. The radiant wall system achieved significant energy savings at set-points 24 ºC and 26 ºC, however, at set-point 22 ºC the radiant walls consumed more energy than the reference. This was caused by the small temperature gradient between the boreholes and the set-point. Figure 4 shows the temperatures in the boreholes and its variation during activation periods. These temperatures tended to stabilise between 16-18ºC, depending on the depth, when there was no operation. However, these temperatures tended to raise about 1.5 – 2 ºC during operation. As a result, the temperature gradient between the boreholes and the set-point (22 ºC) was limited to 2-3 ºC. Consequently the system needed high flows to achieve the required cooling power. This resulted in high electrical energy consumption despite the shorter operation time of the radiant wall compared to the air-to-air heat pump.

Figure 4 also shows the long term behaviour of the boreholes. It was observed that upon consecutives activations the temperatures in the boreholes did not drop down to stability values. However, there is not actual heat storage. Even with consecutives continuous operation test during June and July the minimum temperature between activations at any depth increased less than 0.5 ºC. Furthermore, after one week without operation the borehole temperatures at all depths returned to stability values: The only exception was the temperature at 5 m deep, which increased by 0.5 ºC along the summer campaign. In this case the increase might be related to solar heat accumulation.

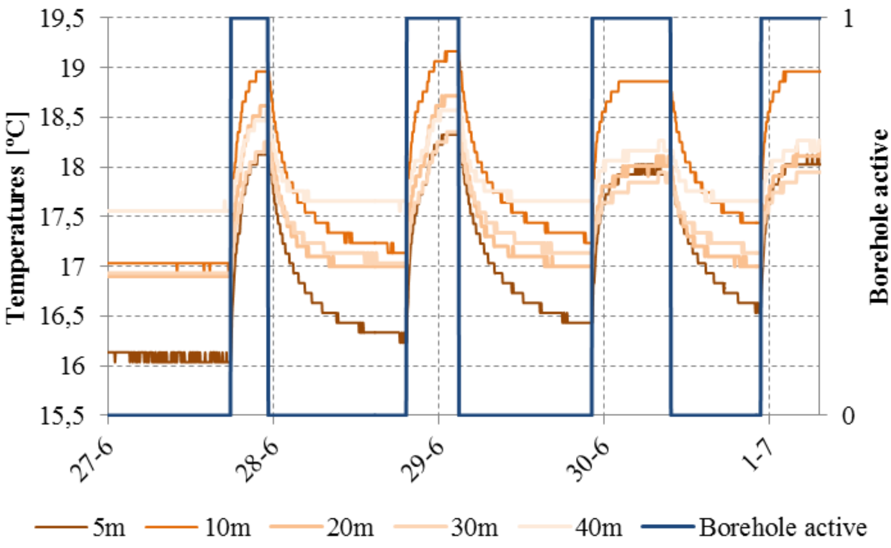


Figure 4: Boreholes temperature profiles during continuous operation cooling test at set-point 24 ºC

4.2 *Night-time charging*

During the night charging test, both systems operated during all the activation period. The air-to-air heat pump of the reference cubicle did not manage to reduce the temperature down to 22 ºC. It maintained an average operative temperature higher than the radiant cubicle, as shown on Figure 5. Furthermore, the reference cubicle had higher temperature raise during the day. As marked by area “a” on Figure 5, during the first instants after the heat pump has stopped a fast raise in the operative temperature occurred. This was followed by a continuous increase of the temperature along the day, which is highlighted in area "b" on Figure 5. This behaviour can be related to the fact that air-to-air heat pump mainly cooled down the room air and it barely extracted heat from the wall. Consequently, when the heat pump stopped the heat stored into the walls was released into the room. In contrast, the radiant wall system extracted heat directly from the wall. That was reflected in more homogeneous temperatures between the room air and the mean radiant temperature. This difference in behaviour is shown on Table 3, as the reference cubicle has higher temperature raise but it also has significant difference between room air temperature gradient and mean radiant temperature gradient. On the other hand, the radiant wall cubicle had an almost constant temperature raise among air temperature, mean radiant temperature and, consequently, operative temperature.

In terms of comfort, the acceptable temperature range considered was 21 - 25.5 ºC. This was obtained according ISO 15251 category I. The reference parameters were taken for offices or residential building considering adaptable clothing between ~1 and ~0.5 [31]. The data summarized on Table 4 shows that the reference cubicle always stayed at a higher temperature range during most of the time. While the reference was kept between 23.5 and 25.5 ºC for more than 75 % of the time, the radiant cubicle stayed between 21 and 23.5 ºC during almost all the test. The higher average operative temperature and the higher temperature raise caused the reference cubicle to exceed the comfort limits 20.18% of time while the radiant cubicle stayed always inside comfort range.

The radiant cubicle maintained better comfort conditions, but it consumed about five times more energy than the air-to-air heat pump. As it happened on the continuous operation test at set-point temperature of 22 ºC, the low temperature gradient between the boreholes and the set-point required a high water flow to obtain sufficient cooling power. However, the temperature raise in the radiant cubicle did not cover all the comfort range. Therefore, a higher set-point temperature for night-charging would still have kept comfort conditions during all the day. Despite the set-point of 22 ºC was set to make use of all the comfort range (21 - 25.5 ºC) the temperature raise was so small that was unnecessary to start with such a low temperature. A higher set-point would have allowed a better performance of the radiant system. Furthermore, these results show that the controller did not fully exploit the radiant wall assets. A better control strategy would take into account the thermal lag and the heat buffering of the radiant wall. Furthermore, a flexible set-point temperature according to predicted heat gains would further optimize the controller.

Table 3: Temperature gradients in night-time charging test on 28/08/2015

	Operative Temperature [ºC]	Mean Radiant Temperature [ºC]	Air Temperature [ºC]
Radiant	1.8	1.7	1.9
Reference	2.5	2.1	2.9

Table 4: Time distribution of operative temperature ranges in night-charging test

Temperature range (ºC)	Radiant cubicle		Reference cubicle	
	h	%	h	%
<21	0	0	0	0
21-23.5	147.67	94.61	6.50	4.16
23.5-25.5	8.42	5.39	118.08	75.65
>25.5	0	0	31.50	20.18

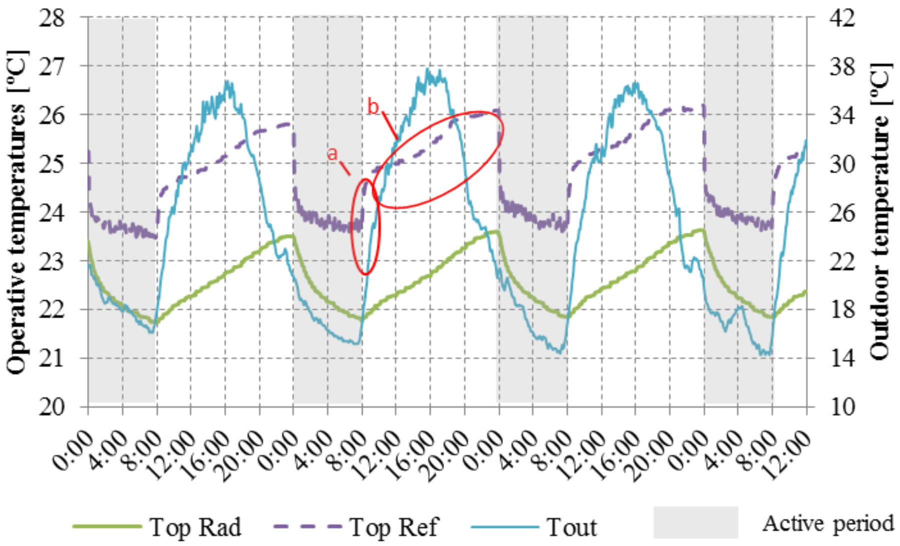


Figure 5: Night charging test operative and outdoor temperatures profiles

4.3 *Occupancy schedule test*

The restricted schedule operation time to occupancy schedules reduced the advantages of radiant wall coupled to ground heat exchanger. As a logic consequence of the limitation of the operation time, the reference cubicle reduced significantly the energy consumption compared to continuous operation test at the same set-point temperature. Table 5 shows that the air-to-air heat pump still operated nearly during all the available activation time, both in domestic and office schedule.

In the domestic schedule test, the radiant wall system operated exactly as it did in the continuous operation. In contrast, the reference cubicle did not only reduce the operation time, but it operated only in energy efficient periods, when the outdoor air was cooler and the heat-pump had a better performance. Table 5 shows that as a result of these conditions the radiant wall did not manage to save energy compared to the reference cubicle. That was caused by the reference reducing significantly its energy consumption while the radiant wall operated very similarly to continuous operation tests but without taking advantage during morning hours of the cold stored in walls during nighttime.

On the office schedule both cubicles had a similar behaviour, as shown on Figure 6. The response time and the trend of the operative temperature were very similar. In this case the radiant wall cubicle operated during most of the activation time, which contrasts with the results in other tests. A cause to this situation was that in this schedule the thermal inertia of the walls was detrimental. The peak load was placed outside the operation time and consequently the cubicle warmed up during the non-active period. At the beginning of the activation period both systems had to do a great effort to remove the accumulated heat, thus having high energy consumption. Furthermore, the air-to-air heat-pump on the reference cubicle was forced to operate with high outdoor temperatures, thus at low energy efficiency. Despite these less optimal operating conditions, the radiant wall cubicle used less energy than the reference, as summarized in Table 5.

The results on occupancy schedule test highlight the importance of the operation strategy in systems with high thermal inertia. This is the asset that gives the radiant wall its peak load shifting capacity. However, the thermal inertia can be detrimental in scenarios when comfort is suddenly required and the systems have to satisfy the cooling demand rapidly.

Table 5: Domestic and office schedule test activation times and energy savings

	Domestic schedule test (24 º)		Office schedule test (24 ºC)	
	Energy (kWh)	Savings (%)	Energy (kWh)	Savings (%)
Radiant	8.165	-7.85	2.784	20.21
Reference	7.571		3.489	

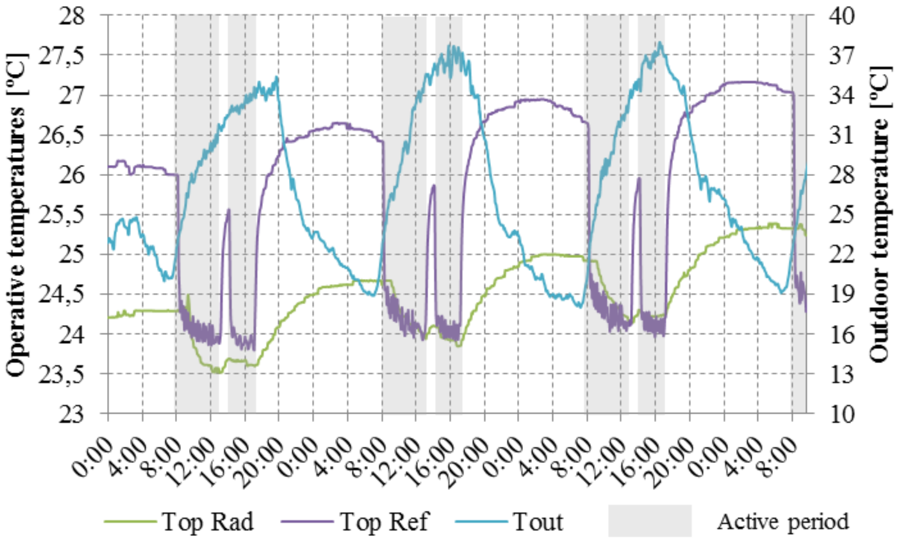


Figure 6: Office Schedule operative temperatures and outdoor temperatures profiles

4.4 *Free floating test*

On the free-floating test, without active cooling, the behaviour of both cubicles was similar. The reference cubicle maintained an average operative temperature 1 ºC higher than the radiant cubicle, as shown in Figure 7. Additionally, the temperature raise due to heat gains during the day was also higher in the reference cubicle. This difference of behaviour was caused by the ventilated facade of the radiant cubicle, since it appears that in cloudier and colder days the operative temperature in both cubicles tended to match better than in sunny days. This can be explained by the ventilated facade helping to reduce heat gains due to high outdoor temperatures and solar radiation.

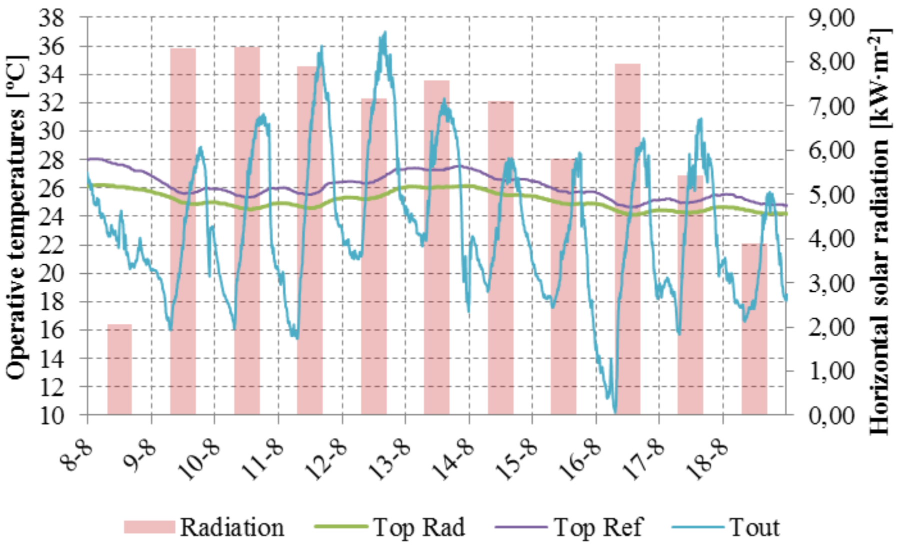


Figure 7: Operative temperature, outdoor temperature and solar radiation on free-floating test

5 Discussion

The presented system showed the potential of free-cooling in a climate with a hot summer and mild cold winter, Csa climate according Köppen-Geiger climate classification [33]. The average ground temperature is at 17ºC, which is cold enough to achieve cooling if using a radiant cooling system. These conditions for the ground are similar to those in Li and al. simulation [5], where the ground temperature is also 17ºC and the results showed that the system achieved a supply temperature of 20ºC, enough to keep the operative temperature of an office building in comfort range for most of the time. In contrast, Ogasawara et al. [6] studied the free-cooling potential in a cold climate for a building with high internal gains. Here, the results showed that free-cooling could deal with most of cooling loads even during summer. However, none of these studies showed the influence of the set-point on the performance of the radiant system coupled to ground heat exchanger. As pointed previously, the set-point is key to obtain energy savings with free-cooling, as low set-points require high flows which might results in significant increase in energy consumption.

Regarding the peak load shifting capacity, the tests showed how the thermal mass of the radiant wall could be exploited for pre-cooling. However, it was also observed that depending on the operation schedule, the thermal mass could be detrimental to the system performance. In that sense, the peak load shifting of TABS was already pointed in the 90's, when night-time pre-cooling was applied to an office building [19], although in that case cooled concrete slabs were used. On a radiant floor similarly controlled to the presented case but coupled to dehumidification ventilation [17], the results showed a similar behaviour. The cooling system had to maintain the set-point the whole day, but it only supplied cooling for a period along the day. This period was lagged with the outdoor peak temperature, as observed in continuous operation test for the radiant wall. A laboratory study testing a radiant system similar to the tested radiant wall showed that concrete core radiant systems exposed to outdoors significantly shifted and shaved the peak load [16]. The results on the current paper agree with these results, though further point on the effect of operation schedule and the dynamics of the system was shown. Despite the thermal mass of the radiant wall could be used for pre-cooling, the results show that the operation schedules are key to achieve good overall performance of the system. Finally, in contrast to previous research which took into account pipes-embedded in concrete, the radiant wall showed that this technology and its advantages can also be applied to brickwork walls.

Furthermore, the comparative study between the radiant wall cubicle and an equivalent reference cubicle with commercial available technologies has been essential to assess its potential, not only providing detailed information regarding its performance, but quantifying the nergy benefits when used in a specific climatic area. The pilot plant experimentation in real outdoor conditions limiting the factors influencing to its performance, no windows or occupant behaviour disturbed the test, highlighted the characteristics of the envelope, leading to a better knowledge of its behaviour.

6 Conclusions

A radiant wall cubicle with a coupled ground heat exchanger and a reference cubicle were built and experimentally tested. A complete set of tests was done during the summer campaign with the objective of comparing the behaviour and energy consumption of the cubicles in cooling mode. The performed tests covered continuous operation at different set-point temperatures, occupancy schedule operation times, night-time pre-cooling, and free-floating conditions. This experimentation gave comparative information about the parameters that most affect the radiant wall performance. It also gave hints towards the best control strategies. However, it was beyond the scope of the paper to calculate the potential of seasonal energy savings, as the short duration of test and its diversity did not allow this calculation. Consequently, the economic and environmental feasibility of the system were not analysed.

The radiant wall system coupled to ground heat exchanger showed high energy savings potential in cooling mode. The reduction of electrical energy consumption was sensitive to set-point temperature because of the limitation of the temperature in the boreholes, which were around 17 – 18 ºC at the test-site. Selection of the set-point for cooling and the temperature fluctuation allowance is essential to obtain high energy savings with the radiant wall coupled to a ground heat exchanger.

On top of the energy savings the radiant wall showed a potential of peak load shifting and night-time pre-cooling. This allows for operation on low cost periods thus adding reduced operation cost to the already reduced energy consumption. This result comes from the better activation the thermal mass achieved with the radiant wall, which stores more energy than a conventional cubicle with an air-to-air heat-pump.

Limiting the time of operation to occupancy schedules reduced the advantages of the radiant wall coupled to ground heat exchanger compared to the air-to-air heat pump. The reference cubicle reduced significantly its consumption as it operated for less time. In contrast, the radiant wall cubicle consumed proportionally more energy because it operated for longer fraction of the activation time. Furthermore, on certain schedules the thermal inertia of the wall ended up to be detrimental.

Despite the peak load shifting capacity of the radiant wall and the significant savings on certain conditions, the controller tested did not exploit the full potential of the system. An advanced control that takes into account the dynamic physics of the system and its boundary conditions would be required to achieve optimum performance.

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