Universitat de Lleida

Improvement of building energy efficiency with radiant walls

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TESI DOCTORAL

Improvement of building energy efficiency with radiant walls

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Directors

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Summary

In a context in which the global trend asks for a reduction of CO_2 emissions and a shift to renewable energies, buildings represent 32 % of the global energy use and about 36% of the CO_2 emissions. This huge contribution makes buildings a main target for implementation of energy efficiency technologies and integration of renewable energies. Thermally activated building systems (TABS) are a set of technologies with good potential for achieving these objectives.

This thesis is focused on the less developed of the TABS technologies, the radiant walls, which have the advantage of being efficient for both heating and cooling. Additionally, if placed in the envelope surface, the radiant walls reduce the influence of outdoor conditions to indoor ambient. Finally, the radiant wall directly exchanges heat with the building structure, actively using the thermal mass for energy storage.

The research was based in the experimentation of a radiant wall cubicle. This was coupled to a geothermal system, which worked as a direct ground heat exchanger in cooling mode and as ground source heat pump in heating mode. The test consisted in a comparative study against a reference. The results showed the good energy savings potential and peak load shifting capability of the radiant wall. However, these results were dependant to set-point temperatures and operation schedules, which could be optimized.

Finally, the experimental data was used for the validation of a numerical model of the radiant wall. First, this was used for a parametrical study, indicating the influence of some of the main design parameters to the radiant wall performance. Then, the model was integrated to a full room model, which was used to study the control of a system consisting in the radiant wall as thermal energy storage for a heat pump coupled to a photovoltaic panels array.

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Resum

La situació actual requereix mesures que redueixin les emissions de CO_2 i incentivin la transició cap a l'ús d'energies renovables. En aquest context, els edificis representen el 32 % del consum global d'energia i al voltant d'un 36 % de les emissions totals de CO_2. La gran contribució dels edificis a aquest problema els converteix en objectiu prioritari per a la implementació de tecnologies d'eficiència energètica i per la integració d'energies renovables. Els sistemes tèrmics integrats als edificis (TABS en les sigles angleses) són una tecnologia amb potencial per complir amb aquests objectius.

La tesis es centra en els murs radiants, un dels TABS menys desenvolupats tot i tenir l'avantatge d'un bon rendiment tant per calefacció com per refrigeració. D'altra banda, els murs radiant poden reduir la influència de les condicions exterior a la temperatura interior. A més a més, com tot els TABS, el mur radiant bescanvia calor directament amb la massa de l'edifici, utilitzant-la d'emmagatzematge d'energia.

La recerca es sustenta en la experimentació d'una caseta amb murs radiants. Aquests estan connectats a un sistema geotèrmic, el qual funciona com a simple bescanviador de calor en refrigeració o com a bomba de calor geotèrmica en calefacció. Els experiments es basen en la comparativa amb un sistema de referència. El resultats mostren que el mur radiant té un gran potencial per reduir el consum energètic i per desplaçar els pics de demanda. Tot i això, els resultats depenen dels horaris de funcionament i de les temperatures de consigna, paràmetres que s'haurien d'ajustar per optimitzar el rendiment del sistema.

Finalment, les dades experimentals són la base per desenvolupar i validar un model numèric del mur radiant. En un primer pas, aquest model ha estat útil per determinar l'efecte dels principals paràmetres de disseny en el funcionament del mur. A continuació, el model s'ha integrat a la simulació del control d'un sistema on el mur radiant funciona com a emmagatzematge d'energia per una bomba de calor acoblada a uns panells fotovoltaics.

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Resumen

La situación actual requiere medidas que reduzcan las emisiones de CO_2 e incentiven la transición hacia el uso de las energías renovables. En este contexto, los edificios representan el 32 % del consumo global de energía y alrededor del 36 % de las emisiones totales de CO_2. Esta contribución de los edificios al problema los convierte en objetivo prioritario para la implementación de tecnologías de eficiencia energética y para la integración de energías renovables. Los sistemas térmicos integrados al edificio (TABS en las siglas inglesas) son una tecnología con potencial para cumplir estos objetivos.

La tesis se centra en los muros radiantes, uno de los TABS menos desarrollados pese a la ventaja de tener un buen rendimiento en calefacción y refrigeración. Por otro lado, los muros radiantes pueden reducir la influencia de las condiciones exteriores en la temperatura interior. Además, los muros radiantes intercambian calor directamente con la masa del edificio, utilizándola como almacenamiento de energía.

La investigación se sustenta en la experimentación de un cubículo de muros radiantes. Estos están conectados a un sistema geotérmico, el cual funciona como intercambiador de calor en refrigeración o como bomba de calor geotérmica en calefacción. Los experimentos se basan en la comparativa con un sistema de referencia. Los resultados muestran que el muro radiante tiene un gran potencial para la reducción del consumo energético y para el desplazamiento de los picos de demanda. Pese a todo, los resultados se ven afectados por los horarios de funcionamiento y por las temperaturas de consigna, parámetros que se podrían ajustar para optimizar el rendimiento del sistema.

Finalmente, los datos experimentales son la base para desarrollar y validar un modelo numérico del muro radiante. En una primera etapa, el modelo fue útil para determinar el efecto de los principales parámetros de diseño en el funcionamiento del muro. A continuación, el modelo se integró a la simulación del control de un sistema donde el muro funciona como almacenamiento de energía para una bomba de calor conectada a unos paneles fotovoltaicos.

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Nomenclature

4SiD	Subspace identification method
ARMAX	Autoregressive moving average exogenous method
CFD	Computational fluid dynamics
COP	Coefficient of performance
DST	Daylight saving time
FDFD	Frequency domain finite difference method
FDM	Finite difference method
FEM	Finite elements method
FVM	Finite volume method
GHE	Ground heat exchanger
GPC	Generalized predictive control
GSC	Gain scheduling control
HVAC	Heating ventilation and air conditioning
MPC	Model predictive control
MRI	More relevant identification method
PCM	Phase change material
PV	Photovoltaic
PWM	Pulse width modulation
RC	Resistor capacitor lumped models

TABS Thermally activated building systems

TB Thermal barrier

TES Thermal energy storage

VAV Variable air volume

VTABS Vertical thermally activated building systems

CONTENTS

Universitat de Lleida

CONTENTS

CONTENTS

CONTENTS

LIST OF FIGURES

CONTENTS

Universitat de Lleida

TABLES

1 Introduction

1.1 Motivation

The current situation presents a scenario of continuous increase of the energy demand and greenhouse gases emissions [1], as presented in Figure 1. Furthermore, a significant part of this energy demand is covered with fossil fuels, see Figure 2. These are non-renewable energy sources that are high contributors to greenhouse emissions. Additionally, the estimations alert that depletion of fossil fuels is a possible scenario in a relatively near future.

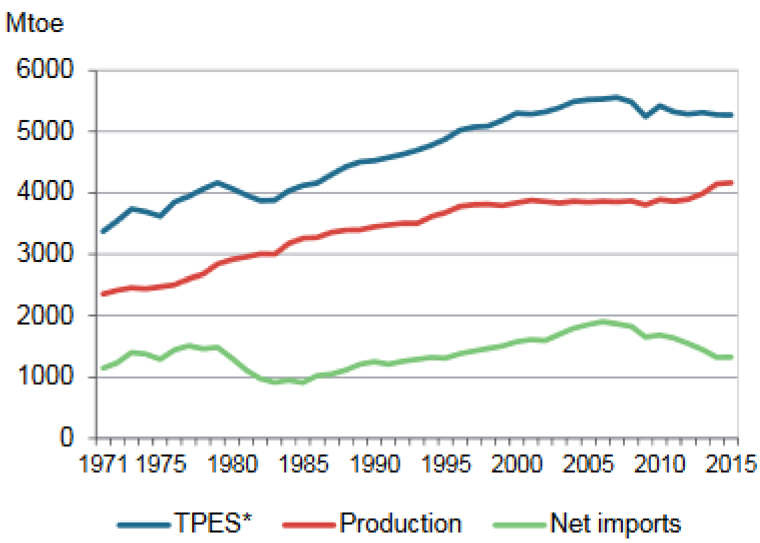

Figure 1. OECD energy supply [1]

In this context, buildings appear as a major contributor to the global energy demand and greenhouse emissions, with 32% of global energy use [2] and about 36 % of CO_2 emissions [3]. Furthermore, far from being a stabilized issue, buildings present an increasing trend in energy use, with energy use growing 1.8% per year from 1971 to 2010 [4] as shown in Figure 3.

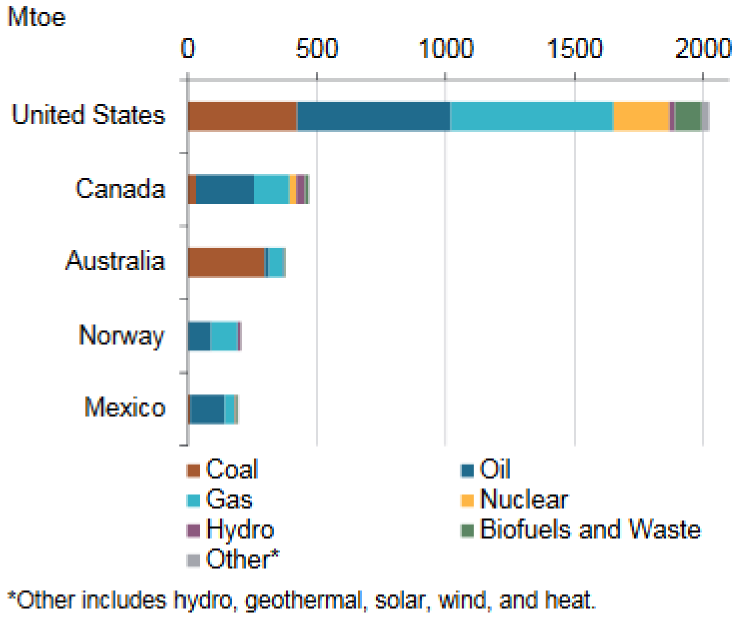

Figure 2. Energy production distribution of top-five PECD producing countries in 2015 [1]

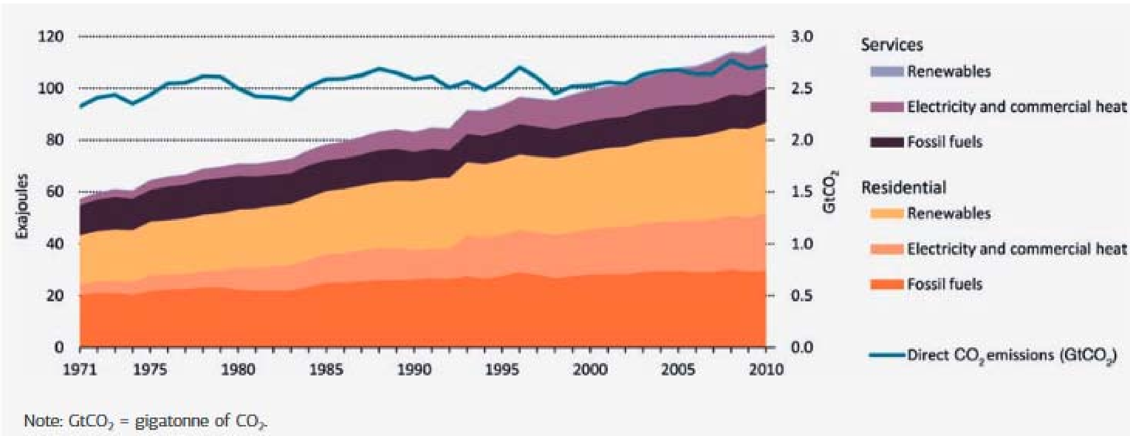

Figure 3. Global buildings energy consumption by energy source and direct CO_2 emissions [4]

This worldwide issue has pushed governments and policy makers to develop policies that promote energy use decrease and reduction of CO_2 emissions. The European Commission targeted for nearly net-zero energy building in 2018 [3], policy which fits with International Energy Agency proposal of reduction of 30% of primary energy use and a decrease of 70% of carbon emissions by 2050 [2]. These policies were recently strengthened by Paris COP 21 agreement [6].

The achievement of these objectives in the building sector faces two main challenges: reduction of energy demand and integration of renewable energies. Fulfilling both objective implies improvement of the envelopes performance, management of solar gains, reduction of internal gains, optimization of building orientations, and improvement of cooling and heating systems performance, among others. However, integration of renewable energies needs to take a step further, as the variable availability of these sources requires capability of management of peak load. This implies integration of energy storage systems. Among all the technologies available, the current thesis studies a radiant wall, a thermally activated building system that can exploit the building thermal mass for storing thermal energy.

1.2 Thermally activated building systems (TABS)

Thermally activated building systems (TABS) are widely studied technologies for the reduction of energy use in building and peak load shifting management [7-11]. The interest on these heating and/or cooling systems integrated into the building structure rose in the 90s [9], as reflected in slab cooling research [12]. However, this is an old technology already used in the Ancient Chinese kang and dikang [13], in the Roman hypocaust [14], or as the widely used Korean ondol [15].

TABS consist of pipes or ducts embedded in the building structure, where the flowing air or water directly exchanges heat with the building thermal mass. Additionally, the building big surfaces are used for heat exchange with the indoor spaces. The concept of TABS can be applied to floors, ceilings, walls, and in-floor slabs, each favouring different operation modes with intrinsic characteristics.

1.2.1 TABS working principles

Two main features define the behaviour and performance of TABS, the availability of big surfaces and the active thermal mass.

1.2.1.1 Big surfaces

By using the building structure for exchanging heat, TABS make use of the availability of big surfaces. This presents a huge advantage, as the convective heat flux depends proportionally on the surfaces, the temperature gradient, and the heat transfer coefficient, as simplified in Equation 1. While the heat transfer coefficient is complex to control, the surface and the temperature gradient can be easily taken into account in the design. Furthermore, both parameters are interchangeable, an increase of surface allows a reduction of the temperature gradient for obtaining the same heat flux.

$$Q = h \cdot \Delta T \cdot S \qquad (1)$$

Where:

- Q: heat [J]
- H: heat transfer coefficient [$J \cdot K^{-1} \cdot m^{-2}$]
- ΔT: temperature difference [K]
- S: surface [m^2]

Consequently, the heating or cooling demand can be achieved at a reduced temperature gradient between the supply temperature and the indoor set-point. This makes TABS suitable for low temperature heating and high temperature cooling [16].

1.2.1.2 Active thermal mass

The pipes or ducts of TABS are embedded into the building structure, therefore, the circulating fluid exchanges heat with the thermal mass of the building. Then, the building surfaces exchange this accumulated heat with the indoor space by radiation and convection. Between these two steps, the heat is accumulated in the corresponding building element, being effectively stored. This feature gives TABS their peak load shifting capability [17], by proper sizing of the thermal mass and adequate positioning of pipes, the building structure can act as short term storage buffering the temperature fluctuations during the day.

1.2.1.3 General characteristics

Beyond of the two main features, TABS have several characteristics that result in different advantages and disadvantages.

First, TABS exchange heat through big surfaces, and thus a significant part of the heat transfer occurs by radiation [18]. This results in a direct control of the mean radiant temperature of the room, which consequently allows management of the operative temperature at a wider range of indoor air temperature [19]. On one side, this results in a better comfort perception, on the other, it reduces ventilation heat loss [20]. As the indoor air temperature can be nearer to outdoor air temperature, the heat loss related to the necessary air exchange is minimized. However, TABS only deal with sensible heat, and thus a complementary ventilation system is required for dealing with latent loads [21]. Although, as TABS fulfil a big fraction of the heating and cooling demand, the ventilation is limited to an air exchange for hygienic reason, this implies a much lower air volume exchange than in heating ventilation and air conditioning systems (HVAC) such as variable air volume (VAV). Therefore, ventilation ducts can be downsized, increasing the available space and reducing both energy use and installation cost [21]. Furthermore, by reducing the temperature and the flow of the air, TABS also reduce the risk of draught and noise. Finally, another advantage comes from the integration to the structure. This frees useful space and can have architectural and aesthetic benefits.

However, the characteristics of TABS also present some disadvantages. Usual building acoustic insulation consists of raised floors and suspended ceilings, these overlap with the more common types of TABS and hinder their heat transfer capacity [9]. Consequently, a compromise between acoustic comfort and TABS performance is required. Furthermore, the surface temperatures are limited by several comfort issues. In case of floors or ceilings, the surface temperature together with the air stratification can cause the disgusting feeling of warm head and cool feet. Finally, the direct contact with surface can also cause discomfort, causing a feel of burning or freezing, the cultural behaviours can have a significant impact on these feelings [23]. Consequently, surface temperatures are limited, which together with the estimated heat transfer coefficients gives an estimation of the maximum heating and cooling capacity of TABS according to the position [18], as summarized in Table 1.

Table 1. Surface temperature boundaries and maximum TABS cooling and heat capacity [18]

		Surface temperature (ºC)		Capacity (W·m^{-2})	
Position		Maximum	Minimum	Heating	Cooling
Floor	Perimeter	35	20	165	42
	Occupied zone	29	20	99	42
Wall		~40	17	160	72
Ceiling		~27	17	42	99

1.2.2 TABS as TES

Despite much research highlights the peak load shifting capacity of TABS [20,24], this technology has just recently been presented as a TES [25]. In this context, TABS mainly store sensible heat, although, some projects also used phase change materials (PCM) [26], adding extra latent heat storage capacity. Additionally, the comfort range limits the storage temperature to low temperature, usually between 21ºC and 26ºC. Moreover, the integration to the building structure limits the storage capacity, and thus TABS only work as short term storage, usually in a daily basis. Finally, a differential feature of TABS is the passive discharging. While charging is done actively with the pipes and ducts, discharging occurs naturally by convection and radiation along the surfaces. As a result, definition of the “charged” status is complex, being the indoor temperature the reference parameter, which has to be maintained inside the comfort range.

To sum up, TABS can be considered as sensible, short term and low temperature TES with the characteristic of being actively charged but passively discharged.

1.3 TABS and integration of renewable energies to buildings

As a result of the peak load shifting capability and the reduced temperature gradient, TABS are a good technology for integration of renewable energies [7].

The reduced temperature gradient shortens the difference between the required supply temperature and some low grade energy sources. In cooling mode, the relatively high supply temperature enables the free-cooling concept, which implies using an ambient heat sink without using any kind of mechanical cooling devices. Therefore, only circulation pumps are used, which have much less energy use than compressors. TABS are used for free-cooling with outdoor cool air during night-time [17,27], ground heat exchangers (GHE) [28,29], and cooling towers [30]. On the heating side, TABS have been used with direct solar heating [31] or with a geothermal heat storage system coupled to low temperature solar collectors [32].

In case the heat sources or sinks cannot provide the required supply temperature, heat pumps can be used the reach the adequate supply temperature level. TABS have good synergy with heat pumps, as the reduced temperature gradient increases the coefficient of performance (COP), therefore the energy use is reduced. As a result, TABS coupled to heat pumps have showed excellent performance in heating with direct solar heat [33] or in both cooling and heating with ground heat exchangers [29,34].

Finally, the management of the peak loads is the key feature in enabling the use of some of the previously mentioned renewable energies. Cooling during the night with outdoor cool air reduced the day loads in a concrete core activated building [17]. Furthermore, TABS can work as the TES of heat pump fed by a photovoltaic array (PV), using the available solar energy to charge the system for maintaining comfort during the rest of the day [33,35].

1.4 Challenges of the implementation of TABS

Due to the peak load shifting capability, TABS have a dynamic nature, usually implying long time constants and slow response times. Consequently, the behaviour and performance of these systems require transient calculations, so that the temperature fluctuation and the stored heat are taken into account. This affects at the design and control of TABS, which can become difficult and cumbersome. Moreover, this dynamic nature cannot be evaluated through simple equations. In this context, modelling is considered as the best solution.

1.4.1 TABS modelling

The modelling of TABS is usually divided into two main applications, design and sizing, or integration to building simulation software and control devices. The first is interested in the heat transfer of the studied TABS, looking for the interaction of all the components and variables. This requires a detailed modelling, explicitly using the heat transfer equations, which is usually referred as white-box modelling. As a result, these models tend to be slow and computationally heavy. On the other side, the integration to building simulation or control devices requires fast models with low computational effort. In these cases, TABS modelling is simplified to the key inputs and outputs, whose relation is determined through some transfer function. These models usually have a black-box or grey-box approach, where the actual physical model is disregarded or simplified.

The detailed modelling of TABS was applied with different techniques, being the most common finite differences models (FDM) [36-38], finite elements models (FEM) [39], and finite volumes models (FVM) [40]. The objectives of these models were also diverse, with studies of the reduction of the cooling load [36], the definition of design charts [37], base cases for simplified model verification [38], parametric studies [39,40], or analysis of comfort and energy consumption [41].

Simplified models reduce the heat transfer to transfer functions or to equivalent electric matrixes, this last usually referred as lumped models or resistor capacitor matrixes (RC). Furthermore, the parameters of these models are usually defined with statistical identification techniques, with black-boxes using pure identification and grey-boxes using a basic reference physical model. Examples of these types of models applied to TABS are transfer functions [42], autoregressive moving average with exogenous (ARMAX) and subspace state space identification (4SID) [43], RC calculated through the components time constants [44], RC calculated with w-RC transform method [45], RC identified with genetic algorithm [46], or model predictive control relevant identification (MRI) [47]. The research involving these methods took in account topics such as model development [43,45,46], integration to full building simulation [42,44], and application to control [47].

All the models imply simplifications of the reality, as it is impossible to take into account all the variables influencing the heat transfer of a complex system. Therefore, modelling requires assumptions and management of uncertainties. In order to accept the accuracy of a model, all the assumptions have to be checked. This requires validation of the simulated results against experimental data or verification with a previously validated numerical model or analytical solution. Furthermore, statistical models require data of the building in order to calculate the model parameters. As a result, part of the modelling research of TABS is dedicated to this topic, for example experimental data was used to validate a FEM model which was later used to verify a simplified RC model [48].

1.4.2 TABS control

The other challenge in the implementation of TABS is the control. This implies defining the supply temperature, the flow, and the length of the activation through the ON/OFF criterion. On the supply temperature side, the most common strategy is the use of heating/cooling curve dependant on outdoor conditions [49]. This is usually the first step of the controller, being a complement of the management of the flow. Regarding the ON/OFF criterion, set-back controls are the simplest option. In those, the set-point temperature is maintained with a dead band regulating the temperature at which the system turns ON or OFF [50]. However, more advanced controls are used to optimize TABS operation. Some examples are the evolution of PID control by gain scheduling control (GSC) [32], or more complex implementations such as pulse width modulation (PWM) [51]. Beyond that, a strong trend is set on controls with forecasting capabilities such as adaptive predictive control [52], generalized predictive control (GPC) [53], or model predictive control (MPC) [47]. These models can predict the status of the TABS system and decide when to charge according to forecasted boundary conditions.

Moreover, TABS only deal with sensible heat and thus need to work together with a ventilation system in order to deal with latent loads. This is relevant to control, as coordination between the two systems is essential to an overall good performance [19]. The coordination avoids the energy squandering caused by both systems working in opposite operation modes [54] and might reinforce the overall capacity of the system [55]. A critical case is TABS used for cooling in humid climates, as the cold surfaces might cause condensation [56], however, coordination of ventilation and TABS greatly minimized this issue [21,55,56].

1.5 Research on the radiant wall (vertical TABS)

The research of TABS is mainly focused on horizontal TABS such as radiant floors, radiant ceiling, or in-floor slabs. However, vertical TABS (VTABS) also present interesting characteristics. In this area, VTABS are referred in various nomenclatures such as active pipe-embedded envelopes [38,46,57-61], thermal barriers (TB) [32,39], thermo active cooling wall [62], vertical thermo active building systems [62], radiant wall panels [63], or radiant walls [64]. Beyond the general TABS characteristics, VTABS present some particularities. First, VTABS present a balanced performance between heating and cooling modes [18], as previously shown in Table 1. Also, when placed on surfaces exposed to outdoors, VTABS reduce the influence of outdoor conditions to indoor temperature by maintaining the wall at a stable temperature [39].

Research on VTABS involved different types of studies. Parametric studies were carried out on active pipe-embedded envelopes with CFD software Fluent [57] or on TB with 3D FEM models [39]. Mainly comparing the system to a conventional wall and analysing the influence of pipes spacing and supply temperature.

A significant part of the research consisted in model development. A CFD model was used for the verification of a 2D lumped model in frequency domain finite difference (FDFD) [38], finding good accuracy of the simplified model with reduced computational effort compared to CFD. This model was further developed by incorporation of genetic algorithm [46] and calculation of heat transfer in the pipe direction [58].

Additionally, any model has to represent a real system, hence the research on the model development led to validation studies. The previously mentioned simplified models [46,58] were compared to experimental data obtained from the same laboratory set-up [59,60]. In contrast, a CFD model was validated with data from experimental research on exposed ceilings with embedded pipes [65]. Finally, a neural network model of a radiant wall was validated with an experimental set-up consisting in a room under laboratory controlled conditions [64].

Alternatively, experimental research was carried out to study the mixed convection on a TB [62]. Other research involved studying the control of a TB with GSC [32] or comparing the performance of radiant heating panels to conventional radiators [63].

Despite all these studies, research on VTABS is lacking compared to other more common layouts. The most remarkable points are the lack of model with actual outdoor data and control studies. In the first part, the experimental studies found in the literature used laboratory controlled conditions [59,60,64,65]. Finally, only one of the studies involved control [32], however, the TB concept used was a system for reducing the heating load instead of a system for providing heating.

2 Objectives

The main objective of this thesis was to carry out a study of the capability of a radiant wall for energy use reduction and integration of renewable energies in buildings. This approach implied obtaining knowledge of an actual radiant wall and then developing tools for studying its design and management. The first step was the comparison of its cooling and heating performance against a conventional HVAC system. Then, the research continued with the study of its TES capability for peak load shifting. Finally, the best options for exploiting the characteristics of the radiant wall were investigated.

Derived from the main objective, the thesis was divided into three blocks: state-of-the-art, experimentation; and simulation. Each of these blocks had the following specific objectives:

State-of-the-art:

- To summarize the status of the TABS technology with an especial focus on vertical TABS.
- To list the main modelling methods applied into TABS simulation and summarize the main research topics and results.
- To present the main trend on TABS control.

Experimentation:

- To determine the energy savings potential of the radiant wall compared to a conventional HVAC system both in heating and cooling mode.
- To determine the potential and limitations of the free-cooling by coupling the radiant wall directly to a ground heat exchanger and comparing it to a conventional air-to-air heat pump.
- To determine the potential of a ground source heat pump coupled to the radiant wall in heating mode compared to a conventional air-to-air heat pump.

- To evaluate the peak load shifting capacity of the radiant wall and the different issues appearing in this operation mode for heating and cooling seasons.

Simulation:

- To develop and validate a numerical model of the radiant wall useful for studying the influence of the design parameters and the control modes.
- To analyse the influence of the main design parameters to the performance of the radiant wall in terms of energy use and comfort.
- To study the control strategies that better exploit the peak load shifting capability of the radiant wall for the integration of renewable energies.

3 Thesis structure

The PhD thesis is based on six papers. Three of them have already been published in SCI journals (papers 1, 2, and 4) and the other three were submitted and are now in peer review process (papers 3, 5, and 6). The structure of the thesis is presented in Figure 4.

This thesis was developed within the research of a radiant wall cubicle built in the GREA experimental test-site of Puigverd de Lleida. The aim of this facility is to increase energy efficiency and sustainability of buildings through the experimentation of passive and active technologies.

The radiant wall was studied within the frame of thermally activated building systems (TABS) technologies. Furthermore, the objectives considered the general performance of the system, its numerical model validation, and the improvement of control. Consequent to this approach, the thesis is structured in three parts.

The first part is the state-of-the-art, which involves paper 1. This is a review that the first summarizes the general characteristics of TABS and then details the different simulation used and the controls applied.

The thesis continues with the experimentation part, which is based on comparative studies between the radiant and the reference cubicles. It consists of 3 papers (papers 2 to 4). Paper 2 describes the cooling performance and capability of the radiant wall cubicle coupled to a ground heat exchanger. This was complemented with paper 3, which studied the influence of internal load the cooling capacity of the radiant wall. At last, the experimental part finishes with paper 4, which presents the results of the heating mode with the radiant wall cubicle being coupled to a ground source heat pump.

Finally, paper 5 links the experimentation with the third part, the simulation. This presents the validation with experimental data of a numerical model of the radiant wall. Furthermore, it summarizes the main findings of a parametric study. Finally, this model is used in paper 6 to study the control options of the radiant wall working with a heat pump coupled to a photovoltaic panels (PV) array.

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CHAPTER III

Thesis structure

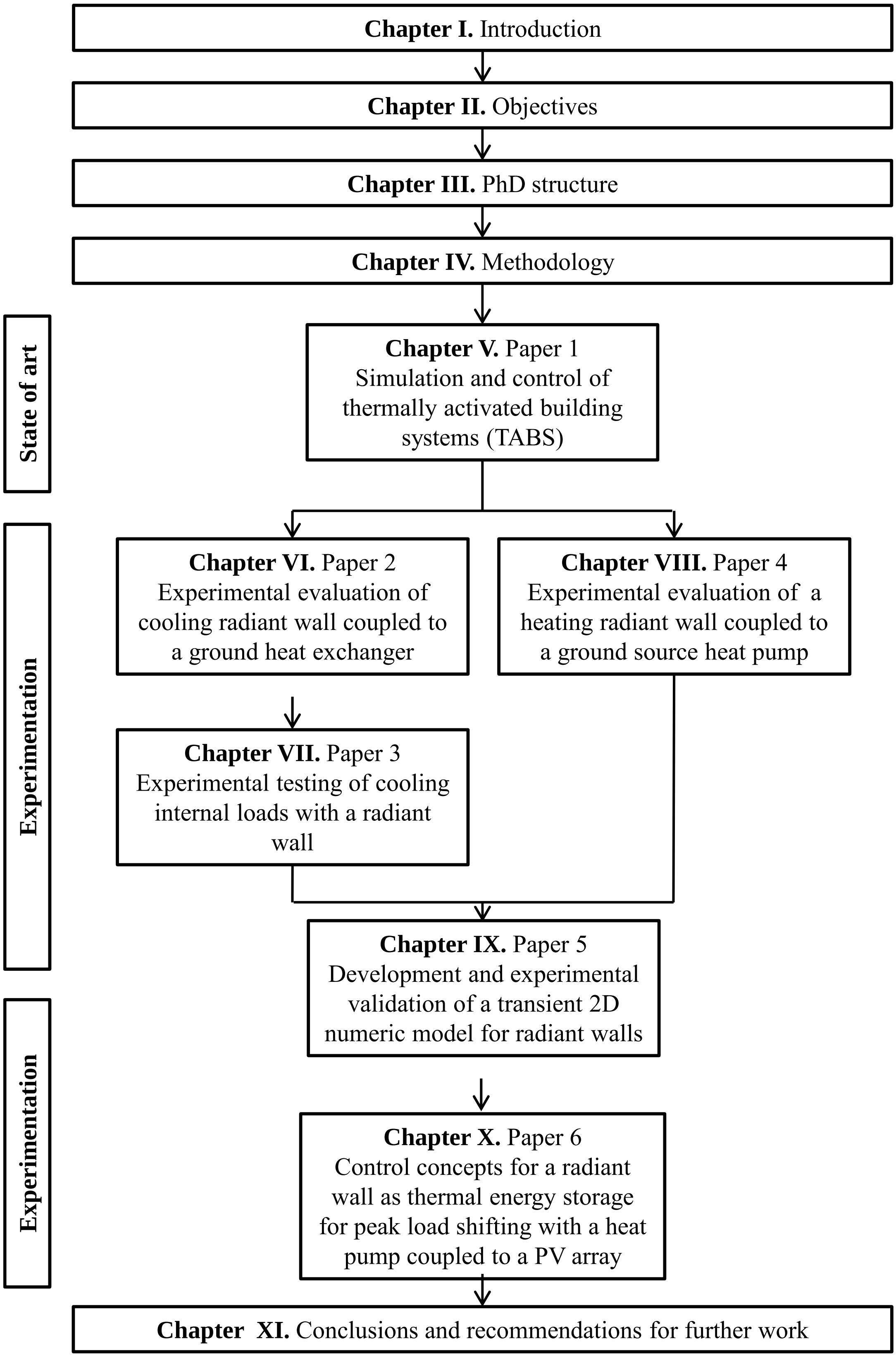


Figure 4. PhD structure

4 Experimental set-up

A very important part of this thesis is the experimentation of the radiant wall cubicle, from which the experimental data was obtained for analysis and model validation. This chapter presents the test site, the characteristics of the radiant wall cubicle and the reference, as well as the construction process.

The experimental set-up consisted in three cubicles built in Puigverd de Lleida (Spain) test site. One was built with radiant wall and supplied with a geothermal heat pump, this cubicle will be referred as “radiant cubicle” along the thesis. The other two were built with conventional techniques and used commercial available air-to-air heat pumps for heating and cooling, these cubicles are referred as “references”.

4.1 Puigverd de Lleida test site

The Puigverd de Lleida (Spain) test site is an experimental facility from the Universitat de Lleida. It consists of 22 house-like cubicles shown in Figure 5, which have been used for testing different building passive and active systems since 2002. The research involved testing of different insulations [66,67], massive building envelopes [68], green roofs [69,70], vertical greenery systems [71-74], rammed earth [75], phase change materials (PCM) for passive cooling [67,76,77], and PCM in actives systems for heating and cooling [78-80]. The weather on the test site is a continental-Mediterranean, which is classified as Csa (warm temperate, dry and hot summer) according to Köpen-Geiger climate classification [81].

Figure 5. General view of Puigverd de Lleida test site (July 2016)

4.2 Preparation of the experimental set-up

The experimental set-up required the construction of a new cubicle and the modification of two existing ones. The preparation of the experimental set-up was divided into three main stages: construction and modification of cubicles, installation and commissioning of hydraulic system, and installation of the monitoring system.

The construction of the radiant cubicle started in December 2014 and was extended until February 2015, when the radiant wall was completed. With the cubicle built, the next stages started. First all sensors were connected to the data logger system. Once connected, correct registering of each sensor was verified and all temperature sensors were calibrated and the monitoring system was prepared. The installation and start-up of the hydraulic system was done in parallel to the preparation of the monitoring system. The cubicles were ready for testing at the end of March 2015, Figure 6 and Figure 7 present all the stages of the construction process.

The experimental set-up was modified in September 2016, the original open joint ventilated facade of the radiant cubicle was removed to obtain data for the validation of the numeric model and for the study of the influence of this component.

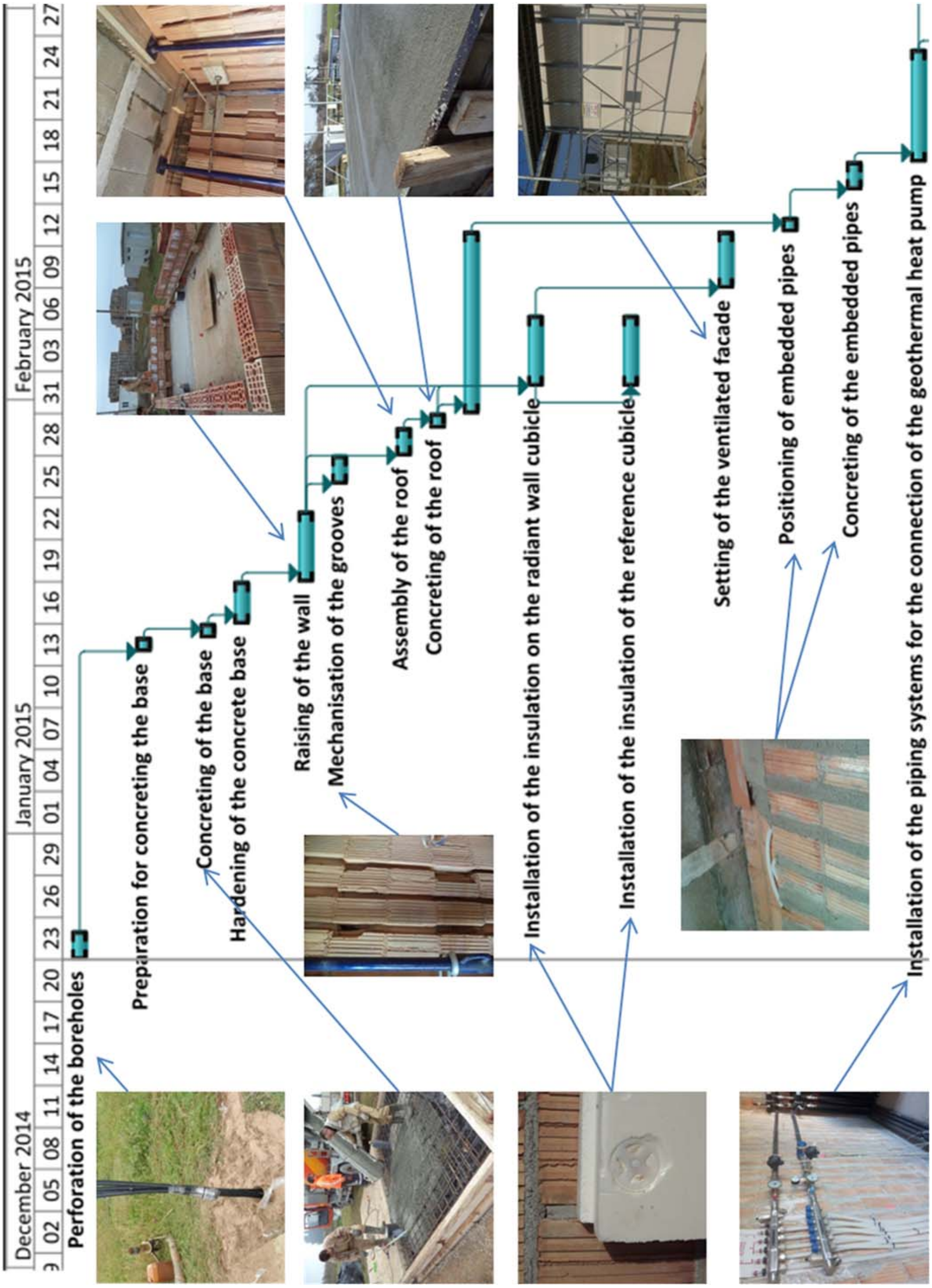


Figure 6. Radiant cubicle construction process (1/2)

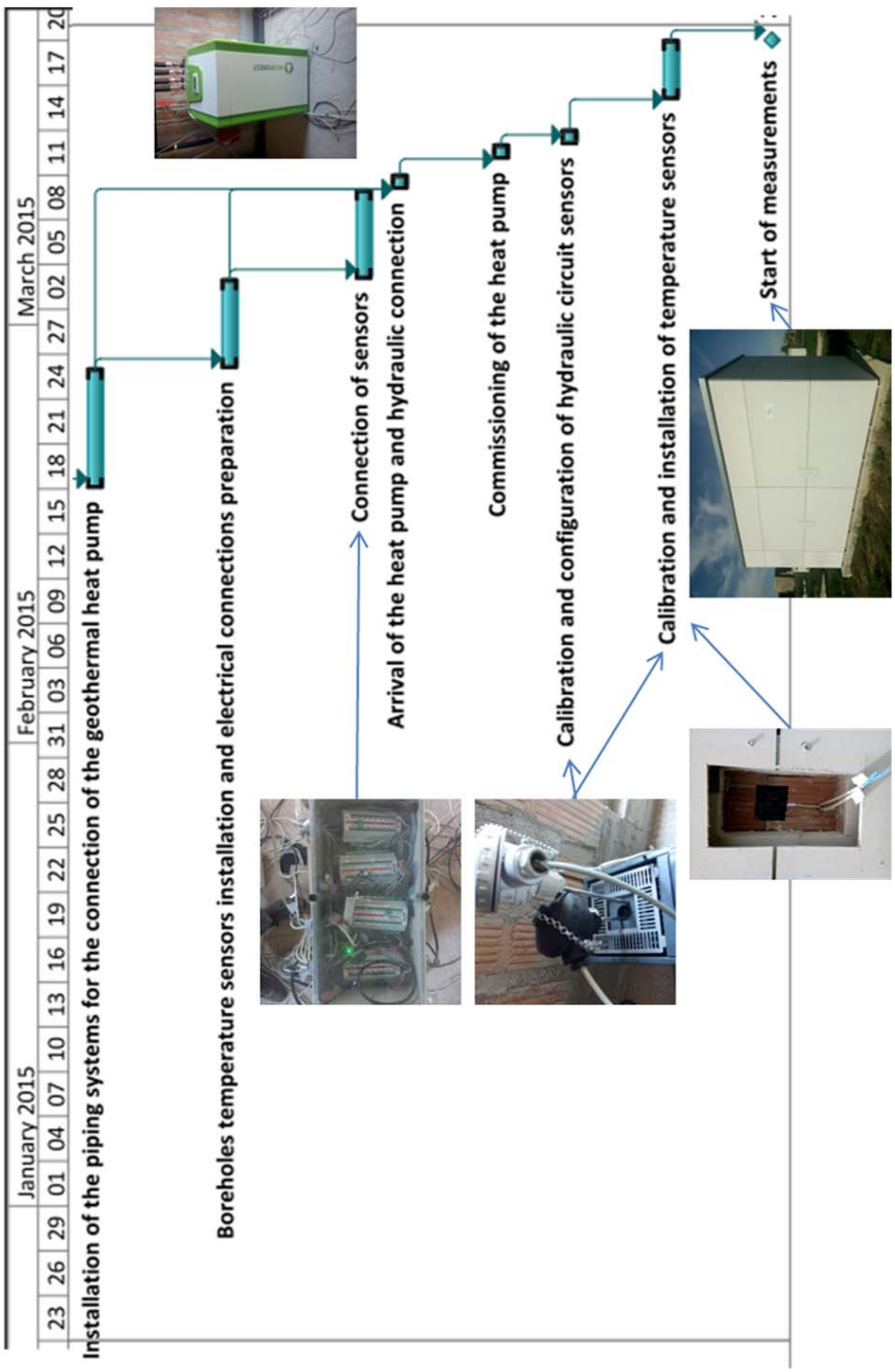


Figure 7. Radiant cubicle construction process (2/2)

4.3 Radiant cubicle characteristics

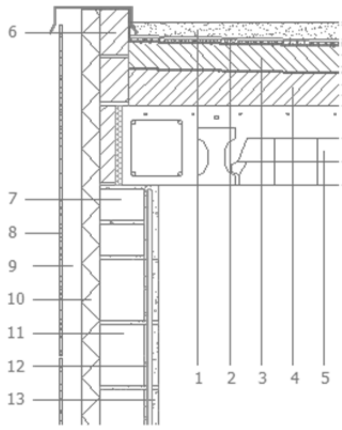
The radiant cubicle consisted of a house-like construction of an internal size 5.25 x 2.7 x 2.7 m, the cubicle at the end of the construction process is shown in Figure 8.

Figure 8. Radiant cubicle in March 2015

The cubicles were built on a reinforced concrete base of 6.2 x 3.7 x 0.25 m. The base served as foundations for the cubicle and insulation from ground. Power and data connection were integrated to the base via underground ducts.

Figure 9. Concrete base during the construction process

The main objective of the thesis was to study the behaviour and performance of the radiant wall. An important aspect to achieve this objective was to minimize the influence of other components, therefore the roof was designed with high insulation in order to minimize heat loss and gains. The structure of the roof was concrete pre-cast beams, which were insulated from outdoors with 50 mm of concrete slab and 80 mm of polystyrene. Another layer of 80 mm of concrete was placed above the polystyrene, this had cement mortar layer with an inclination of 3% to help the evacuation of water. Furthermore, humidity and moisture protection was ensured with a double asphalt membrane. Finally, protection for direct solar radiation was obtained from a 50 mm layer of gravel. Details on wall and roof construction are given in Figure 10.



1 Gravel

2 Double asphaltic membrane

3 Polystyrene 8 cm

4 Cement mortar, flat roof 3 % sloped

5 Concrete precast beams + 5 cm concrete slab

6-7 Hollow brick

8 Ventilated facade panel

9 Ventilated facade channel

10 Polystyrene 6 cm

11 Alveolar brick

12 Polyethylene pipes

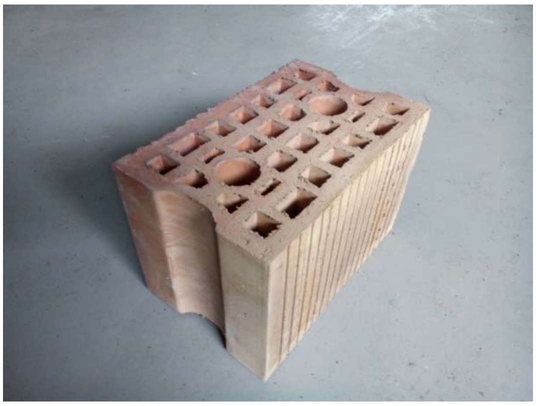
13 Groove for pipe filled with cement mortar

Figure 10. Roof and wall composition (with ventilated facade)

4.3.1 Radiant wall composition

The radiant wall was made with heavy-weight bricks with embedded pipes in the indoor surface. It was insulated and protected from outdoors with a ventilated facade (from March 2015 to September 2016) or a fibrocement panel layer (from September 2016 onwards).

The wall main surface was built with 285 x 185 x 195 mm alveolar bricks, a sample brick is shown in Figure 11. However, two rows of 240 x 150 x 90 hollow bricks were put at the bottom and top part of the wall with the purpose of creating space for the pipes turns, as shown in Figure 11.



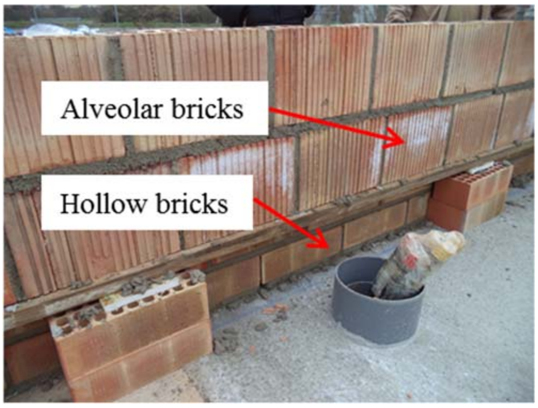


Figure 11. Sample of alveolar brick (left) and structure of the wall (right)

The insulation was made of 60 mm expanded polystyrene panels on the outdoor surface of the wall. The panels were attached to the wall with standard plastic holds to avoid thermal bridges, as shown in Figure 12. More details of the wall structure were presented previously in Figure 10.

Figure 12. Hold of the insulation panels

The radiant system was created with pipes embedded in the indoor surface of the wall. Polyethylene pipes of 16 mm of diameter and 1.8 mm of thickness were placed on vertical grooves cut at 36 mm depth and 150 mm spacing. Good contact between the pipes and the bricks was ensured by filling the remaining space with concrete. The grooves and pipes before and during the process of covering with concrete are shown in Figure 13.

Figure 13. Pipes on groove before and during concreting (left and right respectively)

The radiant wall was divided into five loops of equivalent length to guarantee equivalent flow and heat transfer. One loop was placed in each of the North, East, and West walls, while two were placed in South wall. North wall could only have one loop because of the doors of the cubicle. The radiant wall indoor surface temperature was homogenized by positioning the flow and return of the pipes in alternate grooves. Figure 14 explains schematically the pipes distribution and the positioning of the loops. Each loop involved 16 vertical grooves and had approximately 40.5 m of piping.

All loops were connected to two common manifolds, one for supply and another for return. Consequently all loops operated in parallel and with the same supply temperature. Furthermore, the flow on the loops could be compensated with flow regulating valves. The loop connections are shown in Figure 15.

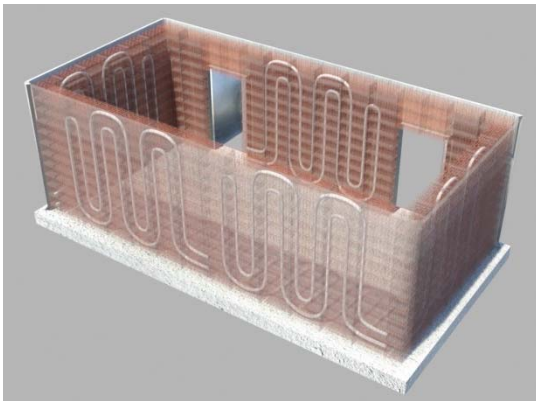


Figure 14. Scheme of radiant wall loop

Figure 15. Radiant wall hydraulic connections

The open joint ventilated facade was used from March 2015 to September 2016. It consisted off a 60 mm air channel created between the insulation and fibrocement panels. The ventilated facade was open in the bottom, top and middle section, as well as in the corners, as shown in Figure 16. The fibrocement panels were supported by S-shaped metal sheets, which divided the ventilated facade in vertical channels.

The ventilated facade was removed in September 2016 and the fibrocement panels were directly attached to the insulation surface, the scheme of the wall with and without ventilated facade is shown in Figure 17.

Figure 16. Details of the ventilated facade, structure (left) and top corner (right)

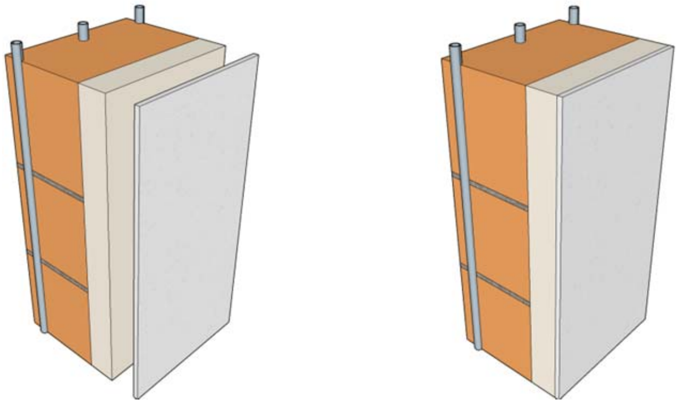


Figure 17. Schemes of the radiant wall with ventilated facade (left) and without (right)

4.3.2 Geothermal system

Heating and cooling was supplied to the radiant wall by an ecoGEO B2 geothermal heat pump [82], which is displayed in Figure 18. This was a water-to-water heat pump with a nominal heating power of 1.4 kW electric and a coefficient of performance (COP) of 4.6. However, on cooling mode it operated only as a heat exchanger between the geothermal system and the supply system. In this mode, the ground was used as a heat sink without the use of a compressor in what was called “free-cooling” mode. This operation mode only used the circulation pumps, with a high energy saving potential.

Figure 18. Geothermal heat pump

The geothermal side of the heat pump consisted of two boreholes, each containing two U-pipes of 20 m and 40 m deep each. The ground on the test site consisted of alternative layers of gravel and clay, a summarized in Table 2. Moreover, it was characterized by a high water table and an undisturbed soil temperature around 17 ºC. Preliminary test showed that the ground was unsuited for thermal storage.

Table 2. 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

4.4 Reference cubicle characteristics

The radiant wall was built with the same internal size as the previously existing cubicles, however, slightly different alveolar bricks were used to ease the installation of the radiant wall. Furthermore, the radiant wall cubicle had extra insulation to maximize the performance of the radiant wall. Consequently, two previously existing cubicles were modified to have equal envelope thermal transmittance in steady-state (U value) by adding insulation. Furthermore, the reference cubicles were equipped with Fujitsu ASHA07LCC air-to-air heat pumps (AAHP) which had a nominal heating power of 3 kW with a COP of 4.55 and a nominal cooling capacity of 2.1 kW with a COP of 4.47. On the other side, the doors and the roof were built with exactly the same system as in the radiant cubicle. Therefore, the only differences between the cubicles were the heating and cooling system and the external ventilated facade.

4.5 Sensor set-up of the cubicles

The objectives of the thesis involved comfort and energy savings measurements, furthermore, validation of a numeric model was required. Consequently the monitoring system had to allow registering parameters of the energy use, indoor temperature, and outdoor conditions, as well as it had to allow calculation of mean radiant temperature and thermal power supplied by the heat pump. Finally, it had to provide temperature profile of the wall for the model validation.

Each loop of the radiant wall had four temperature sensors. The sensors were placed at the centre of the loop and aligned between the wall layers. With the ventilated facade, the positions of the sensors were on the indoor surface, on the surface between the brick and the insulation, in the air channel and on indoor surface of the ventilated facade panels. After the modification of the cubicle, the last two sensors were placed on the surface between insulation and the fibrocement panels and on the outdoor surface. Note that indoor surface sensors were placed at the half distance between pipes. Distribution of sensors in the wall with the ventilated facade is shown in Figure 20.

For the monitoring of the energy use and supply system performance, the electric energy use of the heat pumps was measured with energy meters. The thermal power on the boreholes side and the supply side was measured with pulse flow meters and temperature sensors on the flow and return pipes. As all loops of the radiant wall converged to the same manifold, see Figure 15 in chapter 4.3.1, the thermal power could only be measured as the total heat flow. Furthermore, the temperatures in the boreholes were measured at 5, 10, 20, 30, and 40 m depth.

The indoor conditions of the cubicles were monitored with indoor temperature and humidity. For the outdoor conditions, temperature, humidity, global horizontal solar radiation, and wind speed and direction were measured.

The monitoring of the reference cubicles only required measurements of indoor conditions and energy use, and thus the sensors were limited to indoor air temperature, humidity, indoor surfaces temperatures, and electric consumption.

List of sensors for the radiant cubicle, references, and outdoor conditions are shown in Table 3, Table 4, and Table 5, respectively. The positioning of these sensors in the radiant cubicle is shown in Figure 20, Figure 19, and Figure 21.

Table 3. Sensors list for the radiant cubicle

Type of sensor	Number of sensors	Measurements
Pt-100 DIN B calibrated with a maximum error of ± 0.3 ºC	22	Temperatures of Indoor surfaces Brick-insulation surfaces Air channel Ventilated facade Outdoor surface
Sheathed Pt-100 DIN B calibrated with a maximum error of ± 0.3 ºC	12	Temperatures Boreholes Inlet to radiant wall Outlet from radiant wall Inlet to borehole Outlet from boreholes
ELEKTRONIK EE21 with an accuracy of ± 2 %	1	Indoor air temperature Indoor humidity
Circutor MK-30-LCD-RS485 with an accuracy of ± 1 %	1	Electric energy use
Zenner MTKD-N with 1 pulse per litre and maximum operative temperature of 50ºC	2	Water flow

Table 4. Sensor list for references

Type of sensor	Number of sensors	Measurements
Pt-100 DIN B calibrated with a maximum error of ± 0.3 ºC	7	Temperatures of Indoor surfaces
ELEKTRONIK EE21 with an accuracy of ± 2 %	1	Indoor air temperature Indoor humidity
Circutor MK-30-LCD-RS485 with an accuracy of ± 1 %	1	Electric energy use

Table 5. Sensor list for outdoor conditions

Type of sensor	Number of sensors	Measurements
ELEKTRONIK EE21 with an accuracy of ± 2 %	1	Outdoor temperature Outdoor humidity
Middleton Solar pyranometer SK08 ± 5 %	1	Horizontal global solar radiation
DNA 024 anemometer	1	Wind speed Wind direction

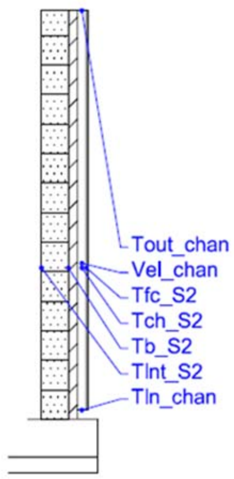


Figure 19. Distribution of sensors in the radiant wall (with ventilated facade)

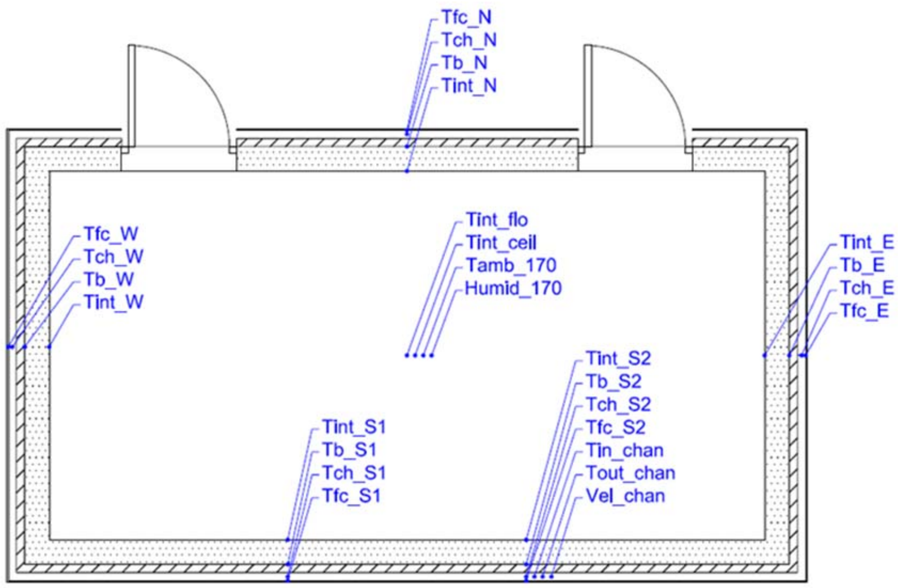


Figure 20. Distribution of temperature sensors in the radiant cubicle

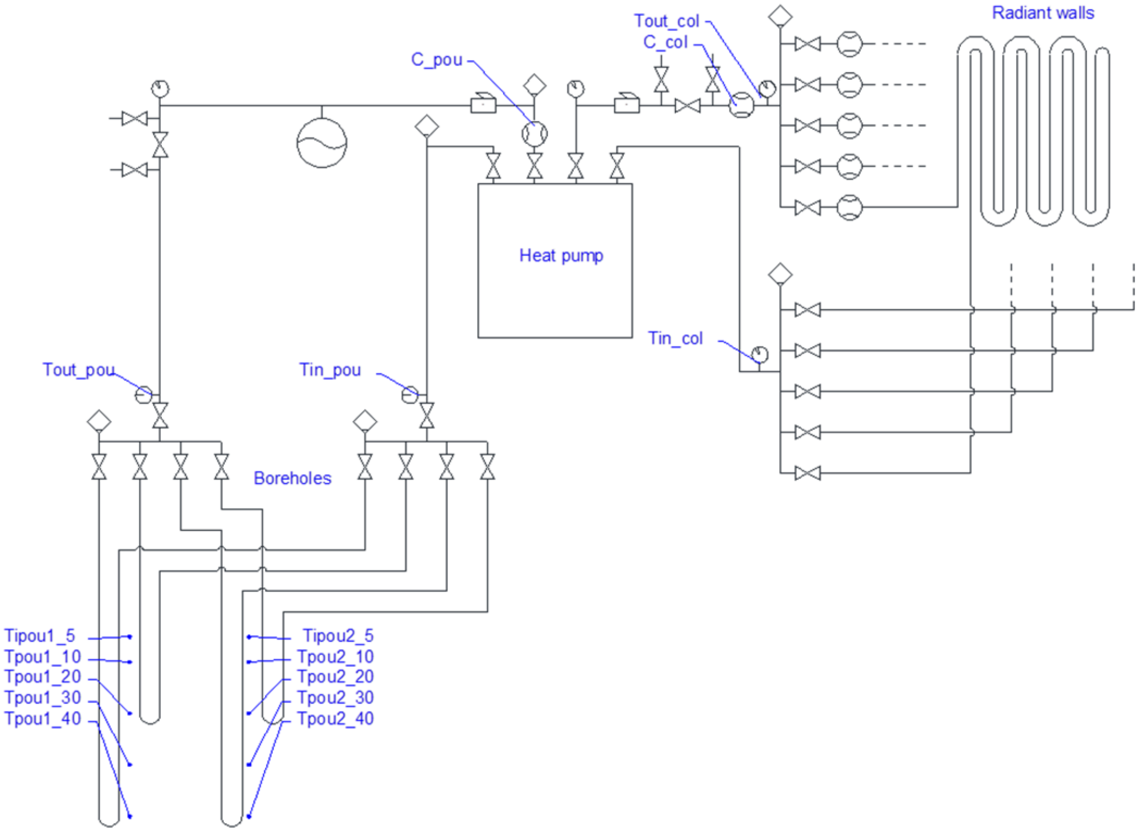


Figure 21. Distribution of sensors in the hydraulic system of the radiant cubicle

4.6 Measurements

The used monitoring system was based on DL01 from STEP.SL. Measurements were taken every 5 minutes and registered in historic files that could later be downloaded as coma separated files (.csv). Furthermore, the data logging system allowed monitoring the current values of the sensors through a synoptic specifically made for each cubicle.

The data logging system took times values according to local daylight savings time (DST), which in Spain corresponds to GMT+2 in summer and GMT+1 in winter. All hourly values in this document are referred to DST.

4.6.1 Operative temperature

The operative temperature represents the uniform temperature of a black enclosure in which an occupant would have the same heat ratio exchange by radiation and convection as in the actual room. Therefore, as the radiant cubicle modified the indoor surface temperature through the radiant wall but the references cubicles did not, the operative temperature was a better parameter than indoor air temperature for the comparison of thermal comfort conditions of both systems. Calculation of the operative temperatures was done according ASHRAE [83] for a point at the centre of the cubicle at a height of 1 m, which matches with the actual placement of the indoor air temperature sensors in the cubicles. Furthermore, only natural convection occurred in the cubicle, and thus air speed was low, which allowed assuming that the operative temperature could be calculated as the average between mean radiant temperature and air temperature, as shown in equations 2 and 3.

$$\bar{T}_r^4 = T_1^4 \cdot F_{p-1} + T_2^4 \cdot F_{p-2} + \cdots + T_N^4 \cdot F_{p-N} \qquad (2)$$

Where

- $\bar{T}_r$: mean radiant temperature [K]

- T_n: surface temperature [K]
- F_{p-1}: view factor of the surface with the reference point (dimensionless)

$$T_{op} = \frac{\bar{T}_r + T_{air}}{2} \quad (3)$$

- T_{op} operative temperature
- T_{air} indoor air temperature

4.6.2 Energy use

The AAHP of the reference cubicles did not have variable speed compressor, consequently, cooling power was regulated by ON/OFF controller. The monitoring system registered measurements every 5 min and the electric meters measured pulses of energy in Wh, therefore, the instant electrical power could not be represented accurately, as the ON/OFF cycles of the AAHP were shorter than the measurement step. Consequently, the consumption of the heat pumps was represented as hourly energy use.

4.6.3 Thermal power

The heat flux absorbed by the radiant walls and the boreholes was calculated assuming that the fluid temperature measured every 5 min could applied to the whole time step. Moreover, thermal properties of water were calculated according this assumption. The energy was accounted for the amount of litres registered for each time step, and thus the power was calculated dividing the heat obtained by the length of the time step.

5 Simulation and control of thermally activated building systems (TABS)

5.1 Introduction

As previously mentioned, TABS are a well-known set of technologies for their potential for energy reduction and integration of renewable energies in heating and cooling of buildings. The rising interest around this technology during the last decades led to many research in the topic. This wide research is reflected in several published reviews. Among them, Xu et al. focused on the integration of low-grade energy sources first with pipe-embedded structures [7] and later with hollow core slabs [8]. Alternatively, Rhee et al. [9] presented an historical overview of the radiant heating and cooling systems, which was recently followed by a review of the key issues of this technology [10]. Similarly, Olsthoorn et al. [11] focused in the peak load shifting capacity, with an especial focus on exploiting this characteristic through model predictive controls (MPC).

Despite all these reviews, TABS research is so wide that the literature can be classified by different topics or interest. Considering that modelling and control are some of the keys point to the development of this technology, the interest of reviewing and classifying the research according to these topics was clearly needed. Furthermore, the lack of a common terminology is a generally identified issue for identifying TABS research [11,19], consequently, summarizing the different terms used for referring to the different types of TABS terms was relevant.

5.2 Contribution to state-of-the-art

In order to better understand the technology and its potential, this chapter first presents an overview of the main characteristics of TABS and a summary of the different nomenclature found in the literature. Then, the focus is set into an extensive review of the modelling methods and control strategies of these systems. The complete review is presented in the following research paper:

- J. Romaní, A. de Gracia, L.F. Cabeza, Simulation and control of thermally activated building systems (TABS). Energy and Buildings 127 (2016) 22-42

First, the review presents a summary of the main characteristics and issues of TABS. This is followed by a classification of the different systems found in the literature that match these general characteristics. The classification is divided into five categories according to the surface position, the working fluid, and the thermal mass: radiant floors, radiant ceiling, hollow core slab, concrete core slab, and pipe-embedded envelopes. A summary of the list is presented in Table 6.

TABS simulation is an important issue in the research and development of this technology. This is reflected in the evolution of the models used and the objectives behind each simulation. First simulations were based in analytical models [84] used for calculation of the heat transfer capacity. However, analytical models only solved a limited number of configurations and those were only valid in steady state. Consequently, numerical models were applied, achieving better accuracy than analytical models and allowing detailed studies of the performance [87]. Currently, the numerical models are still interesting for carrying out parametric and design studies [39]. On the negative side, numerical models tend to be computationally heavy. Therefore, the necessity of integration of TABS models in full building simulations required lighter models. A first solution was the implementation of semi-analytical models to building simulation software that at the time used 1D analytical models [86]. Later, transfer functions were also proposed [42]. The increasing interest of the simplified models also led to lumped resistor capacitor models (RC), both with analytically defined parameters [44] or statistically identified parameters [46]. This last type of modelling based on measured data and statistical methods also drew wide interest, resulting in the implementation of different method to TABS simulation [43,47].

Table 6. Summary of TABS nomenclature (summarized)

Type	Specific nomenclatures	Acronym
Radiant floors	Concrete slab floor	-
	Floor heating	-
	In floor radiant systems	-
	Radiant cooling/heating	-
	Radiant floor	-
	Radiant floor conditioning	RFC
Radiant ceiling	Ceiling embedded piping	-
	Ceiling panels	-
	Ceiling radiant cooling	-
	Ceiling radiant cooling panels	CRCP
	Ceiling radiant panels	-
	Cold radiant ceiling panels	-
	Cooled ceiling	-
	Cooling panels	-
	Core cooled concrete slab	CCCS
	Hydronic radiant cooling	HRC
	Hydronic radiant panels	-
	Radiant ceiling	
	Radiant cooling/heating	-
	Radiant hydronic slab	-
	Radiant slab system	-
Hollow core slabs	Active hollow core slabs	-
	Hollow core slabs	-
	Ventilated slab	-
Concrete core slab	Concrete core activation	CCA
	Concrete core cooling/heating	-
	Concrete core conditioning	CCC
	Concrete radiant cooling slab	-
	Concrete slab cooling	-
	Floor-ceiling radiant panels	-
	Pipe-embedded slabs	-
	Slab heating/cooling	-
	Thermally activated concrete slab	-
	Thermo active building system	TABS
	Thermo active components	TABS
Pipe-embedded envelopes	Active-pipe embedded envelopes	-
	Thermal barrier	TB
	Thermo-active cooled wall	-
	Vertical thermo active building systems	VTABS
	Wall panels heating	-

On the control side, heating/cooling curves and set-back control are the base case for control strategies. As such, some research was carried out to define the process for determining the adequate heating/cooling curves [88]. Regarding the set-back, the first part of the research studied the influence of the set-points and dead bands on the performance of set-back controls [89]. This was further extended with studies calculating the adequate length of the activation periods [90]. Finally, the availability of models with light computational effort allowed the implementation of predictive controls, capable of predicting the system status according to forecasted boundary conditions [30].

The review presented a general view of the potential of TABS, emphasizing the tools developed for their research and evolution of the control strategies.

5.3 Contribution of the candidate

The candidate was in charge of carrying out the literature review following the established topic and key-words of the project. The gathered information was classified and structured in a series of meetings, after which the candidate was responsible to lead the writing of the paper.

5.4 Journal paper

Energy and Buildings 127 (2016) 22–42

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Review

Simulation and control of thermally activated building systems (TABS)

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ABSTRACT

Buildings account for a significant amount of global energy use and CO_2 emissions. Thermally Activated Building Systems (TABS) are a technology with potential for significantly reducing buildings energy use. TABS are heating and cooling systems that are integrated in the building structure. They mainly exchange heat through radiation and are able to store heat in the building thermal mass. TABS high thermal mass and their interaction with the building structure make their energy evaluation and design process difficult. Development of simulation models has been essential to study the design and control of TABS. Control of TABS is challenging due to the slow response time and storage capacity. A lot of research has been conducted to develop control strategies that fully exploit its energy saving potential and that maximize the use of renewable energies. This paper summarizes the main characteristics of TABS and presents the developed simulation models and control strategies.

J. Romaní, A. de Gracia, L.F. Cabeza, Simulation and control of thermally activated building systems (TABS). Energy and Buildings 127 (2016) 22-42 DOI: 10.1016/j.enbuild.2016.05.057

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

6.1 Introduction

As described previously, the big surface and the efficient heat exchange of the radiant wall allow for high temperature cooling [17]. The undisturbed ground temperature in the Puigverd de Lleida test site was around 17 ºC, which was low enough for a borehole to supply water for cooling the radiant wall without requiring a compressor chiller [28]. Supplying cooling with this system only requires energy use for the circulation pumps, which consume relatively low power compared to a compressor chiller, therefore, the radiant wall coupled to a ground heat exchanger have the potential to save energy. However, such a system does not allow for regulation of the supply temperature, as this is bonded to ground temperature. Consequently, the cooling capacity cannot be regulated, which might affect its performance.

In summer the outdoor conditions vary from temperatures below indoor set-point during night periods to temperatures above indoor set-point during day time. This causes a daily alternation of heat gains to heat loss from and to outdoor ambient. Furthermore, the solar radiation heats up the envelope of the cubicle during the day. The combination of high outdoor temperature and solar radiation cause a peak of cooling load, however, the thermal mass of the envelope buffers and delays the heat wave to the indoor space. A passive heavy weight wall can buffer the heat wave and passively release to the outdoor ambiance during night period, and thus reducing the cooling load. In contrast, the radiant wall directly removes the heat from the envelope, limiting the heat gains by keeping the wall at a lower temperature [57]. Furthermore, this storage capacity is useful for shifting the peak loads.

This chapter presents the study of the capability for energy savings of the radiant wall cubicle coupled to a ground heat exchanger compared to an equivalent heavy weight wall cubicle cooled down by a conventional air-to-air heat pump. The interaction of each system with the thermal mass was also evaluated, studying the capability of peak load shifting of each system.

6.2 Contribution to state-of-the-art

The performance of a radiant wall coupled to a ground heat exchanger was compared against an equivalent cubicle with air-to-air heat pump. The influence of set-point temperature, operation schedule and peak-load shifting capacity of systems was experimentally studied. The results of the study were presented in the following research paper:

- J. Romaní, G. Pérez, A. de Gracia, Experimental evaluation of a cooling radiant Wall coupled to a ground heat exchanger. Energy and Buildings 129 (2016) 484-490

This paper showed that the ground temperature on the test site was around 17-18 ºC, which allowed for free-cooling with the ground heat exchanger. As a result, the radiant cubicle achieved significant savings at continuous operation. However, energy savings were very sensitive to set-point temperature, as at low set-point, the temperature gradient between the borehole and the indoor ambiance was limited, so the system had low cooling power and then it required long operation times. Consequently, the radiant cubicle achieved savings at set-points of 24 ºC and 26 ºC, but not at 22 ºC, as summarized in Table 7.

Table 7. Energy savings with cooling on continuous operation

Set-point	Energy savings
22 ºC	-11.12%
24 ºC	54.34%
26 ºC	83.08%

Furthermore, night-time charging test demonstrated the radiant wall cubicle capacity for peak load shifting. While the reference cubicle could not exploit actively its thermal mass, the radiant wall could store heat during the night period and still keep the comfort range during the day without active cooling. Figure 22 shows that the temperature on the reference cubicle increased sharply as soon as the active period finished. This implied that the walls still stored heat from the day gains, as the air-to-air heat pump was unable to remove during night operation. Consequently, the heat stored in the walls heated the indoor space when cooling was switched off, as shown in “a” area of Figure 22. During the rest of the day, the cubicle heated up because of the outdoor high temperatures and solar radiation incident on the cubicle surfaces, as shown in “b” area, In contrast, the radiant wall directly removed the heat from the thermal mass of the building. As a result, the temperature of the radiant cubicle was more stable and only increased due to heat gains during the day.

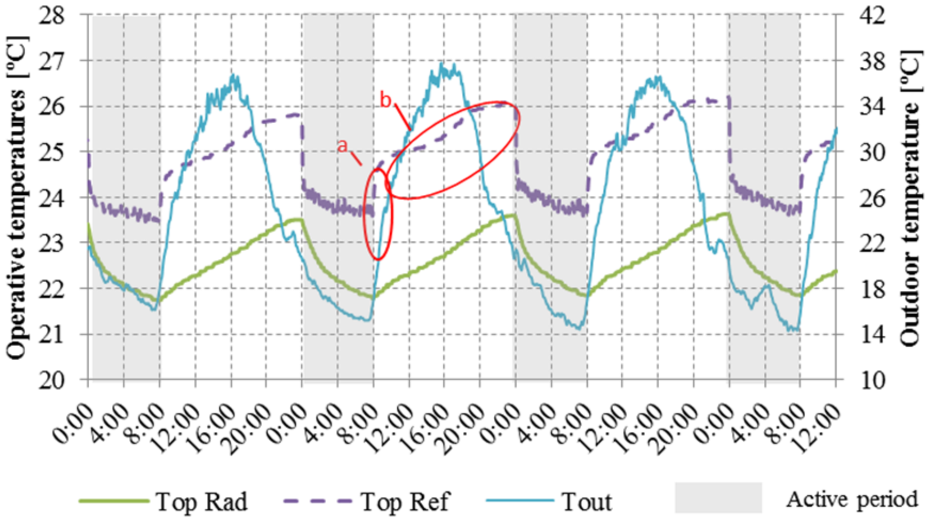

Figure 22. Operative temperatures of radiant cubicle (rad), reference cubicle (ref), and outdoor temperature during night-time operation test

Operating in occupancy schedules reduced the number of hours at which the cubicles has to meet the set-point. In the reference cubicle, this resulted in less operation time of the air-to-air heat pump compared to continuous operation test, as a result, the reference cubicle reduced its energy use. However, the radiant cubicle still had to remove to heat accumulated in the wall before cooling the indoor space, and thus the operation time of the ground heat exchanger was similar than in continuous operation test. Consequently, in these operation conditions the radiant cubicle reduced its energy savings potential. Furthermore, the slow response time of the radiant wall caused to radiant cubicle to achieve the set-point temperature with certain delay.

Finally, the test showed that a control with set-points and dead-band did not fully exploit the potential of a radiant wall. An optimization of its operation would require taking into account the dynamics of the system in order to achieve good prediction of the energy stored in the wall.

6.3 Contribution of the candidate

The GREA research group already had experience in testing active heating and cooling systems, and thus the basic tests and the experimental methodology were already established. Related to the experimental part, the candidate was in charge of maintenance of the test site, experimental tests, data treatment, and analysis. On the paper development, the candidate was in charge of leading the literature review and the writing of the scientific article.

6.4 Journal paper

Energy and Buildings 129 (2016) 484–490

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

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Ground heat exchanger

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 °C and 26 °C, 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.

J. Romaní, G. Pérez, A. de Gracia, Experimental evaluation of a cooling radiant wall coupled to a ground heat exchanger. Energy and Buildings, 129 (2016) 484-490 DOI: 10.1016/j.enbuild.2016.08.028

7 Experimental testing of cooling internal loads with a radiant wall

7.1 Introduction

The previous chapter showed the capability of the radiant wall for energy savings in cooling mode. However, the experimental conditions in that research only took into account heat gains caused by outdoor conditions. Still, some researchers pointed that in well-insulated buildings internal loads are the major contributors to the cooling load [91]. Furthermore, TABS, such as the radiant wall, are especially sensitive to internal loads [92,93].

Additionally internal heat loads follow different daily trends than solar heat gains, depending on the type of occupancy [94,95]. Furthermore, each occupancy profile also requires maintaining comfort conditions during different periods. These issues make exploiting the peak load shifting capability of the radiant wall complex. On one side, the cooling load increases, while on the other, internal gains may overlap with optimal pre-cooling periods.

Complementary, free-cooling with ground heat exchanger does not allow regulating the supply temperature, as the return temperature from the boreholes depends of the ground temperature and the inlet temperature. Consequently, the cooling capacity of the radiant walls coupled to the ground heat exchanger is proportional to the temperature gradient between the supply temperature and the indoor temperature.

The current chapter focuses on the influence of internal gains on the cooling and peak load shifting capacity of the radiant wall in a comparative study with two reference cubicles.

7.2 Contribution to state-of-the-art

The influence of the internal loads to the radiant wall performance was evaluated in a comparative study. The radiant wall cubicle coupled to the ground heat exchanger was compared to two reference cubicles under different internal loads schedules, from continuous internal loads to office and domestic internal loads schedules, and under different control strategies. The results of the research are presented in the following paper:

- J. Romaní, L.F. Cabeza, G. Pérez, A.L. Pisello, A. de Gracia, Experimental testing of cooling internal load with a radiant wall. Submitted to Renewable Energy (July 2017) ref: RENE-D-17-02228

With continuous internal gains the radiant wall coupled to a ground heat exchanger showed its limited cooling capacity. Operating on the design flow, the radiant wall cooling power was proportional the temperature gradient between the supply temperature and the indoor temperature. In these conditions, the radiant wall showed a maximum average cooling power of 750 W in the most favorable conditions. In order to compensate the low cooling power, the system operated for longer activations periods. However, longer activation periods reduced the average cooling power, as the temperatures in the boreholes and the radiant wall tended to converge, decreasing the temperature gradient. Furthermore, the energy use of the circulating pumps was constant, and thus at longer activation periods the radiant wall cubicle had higher energy use than the references.

Despite the high internal load and the hot weather conditions, the radiant wall showed its capability for peak load shifting. In the tests with internal loads following occupancy schedules the radiant cubicle was operated with a pre-cooling strategy, lowering the set-point during night-time. With this strategy the radiant cubicle could achieve operation cost savings even with a higher energy use than the reference, as shown in Table 8.

Table 8. Energy savings with cooling on enhanced operation

	Reference		Radiant		
	Set-point	Energy (kWh)	Energy (kWh)	Energy savings (%)	Economic savings (%)
Office internal gains	26 ºC	13.499	16.570	-18.53	29.70
	24 ºC	20.182		21.80	51.74
Domestic internal gains	26 ºC	14.079	18.450	-23.69	22.83
	24 ºC	20.787		12.67	47.81

7.3 Contribution of the candidate

The maintenance and operation of the test site was under the responsibility of the candidate. Furthermore, the candidate also contributed to the literature review and to the experimental planning. Finally, the candidate leaded the data analysis and the writing of the paper.

7.4 Journal paper

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Experimental testing of cooling internal loads with a radiant wall

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A B S T R A C T

Thermally activated building systems (TABS) consist of pipes or ducts embedded in the building structure. This is a well-known technology for its capability to reduce energy use for cooling buildings. Additionally, TABS help integrating renewable energies, such as free-cooling with ground heat exchangers (GHE). However, TABS cooling load is sensitive to the internal load, and the use of GHE for free-cooling is limited to low energy buildings. In a previously published research, a radiant wall cubicle without internal gains demonstrated to achieve significant energy savings. However, the current research showed that under domestic and office scheduled internal gains equivalent to 42 W m^{-2} the radiant cubicle increased its energy consumption for cooling more than the reference cubicle with air-to-air heat pumps. As a result, the radiant cubicle used around 20% more energy than the reference at air temperature set-point 24 °C but saved around 20% compared to the reference at 26 °C. Despite this, the radiant wall could still reduce the cooling cost through peak load shifting even though it showed to consume more energy than a conventional HP.

J. Romaní, L.F. Cabeza, G. Pérez, A.L. Pisello, A. de Gracia, Experimental testing of cooling internal load with a radiant wall. Renewable Energy 116 (2018) 1-8 DOI:

10.2016/j.renene.2017.09.051

8 Experimental evaluation of a heating radiant wall coupled to a ground source heat pump

8.1 Introduction

In winter the undisturbed ground temperature is higher than the outdoor temperature, furthermore, it does not have the daily fluctuation. This presents an advantage for ground source heat pumps compared to air-to-air heat pumps, as the ground is a heat source at a higher temperature than air, which improves the COP of the ground source heat pump compared to the air-to-air heat pump [96]. Moreover, the radiant wall requires a relatively low supply temperature for heating [7], which combined with the higher temperature of the heat source results in a lower temperature gradient to the heat pump. Consequently, the ground source heat pump coupled to a radiant wall operates in more constant and efficient conditions than an air-to-air heat pump.

On the other side, outdoor temperatures in winter are below indoor comfort temperatures for most of the time, which results in permanent heat loss to the outdoor ambient. Solar radiation can reduce heat loss on the surfaces in which it is incident, although, surfaces without direct solar radiation will still have significant heat loss. As a result, winter causes almost permanent heating demand to a building, which contrasts with summer cyclic cooling demand between day and night. This characteristic makes management of peak load shifting capability of the radiant wall difficult [97]. Charging the wall in off-peaks implies increasing the temperature of the wall, which also increases heat loss to the ambient. Furthermore, low cost periods are usually at night an early morning, when outdoor temperatures are lower.

This chapter presents the study of both the capability for energy savings and the peak load shifting management of the radiant wall cubicle coupled to a ground source heat pump.

8.2 Contribution to state-of-the-art

The performance of the radiant wall cubicle was experimentally compared against two equivalent cubicles with air-to-air heat pumps. The influence of the set-point temperatures was evaluated together with the capability of peak load shifting with different pre-heating periods. The results of the study were presented in the following research paper:

- J. Romaní, G. Pérez, A. de Gracia, Experimental evaluation of a heating radiant Wall coupled to a ground source heat pump. Renewable Energy 105 (2017) 520-529

First, the study highlighted the good savings capability and the good COP achieved with the radiant wall coupled to a ground source heat pump, as summarized in Table 9. On continuous operation the savings were affected by set-point, although minimum of 20 % was achieved at the highest set-point. Moreover, the operation conditions of the heat pump allowed achieving a good overall COP, which was stable around 4 at all tested set-points.

Table 9. Energy savings and COP in heating test on continuous operation

Set-point	Energy savings	COP
22 ºC	40.74 %	4.27
24 ºC	27.08 %	3.96
26 ºC	19.97 %	4.02

On the management side, the study showed that the references could not work on peak load shifting mode. The air-to-air heat pumps were unable to store heat on the thermal mass of the cubicle, and thus temperatures rapidly dropped when the heating supply stopped, as shown in Figure 23. On the other side, the radiant wall had a slower temperature decrease along the day, maintaining the indoor temperature in the comfort range for most of the day. Despite this, the temperatures in the radiant wall also dropped below the comfort level for several hours every day. Furthermore, during the longer pre-heating the heat pump had to reheat the cubicle several times in order to achieve the set temperature of 26 ºC at the end of the charging period, which implied that part of the energy stored was lost to the outdoor ambient during the charging, causing an inefficiency. These tests highlighted the requirement of adjusting the pre-heating period in order to minimize the wasted heat. Furthermore, it also suggested that back-up heating during the day should be allowed to keep comfort conditions.

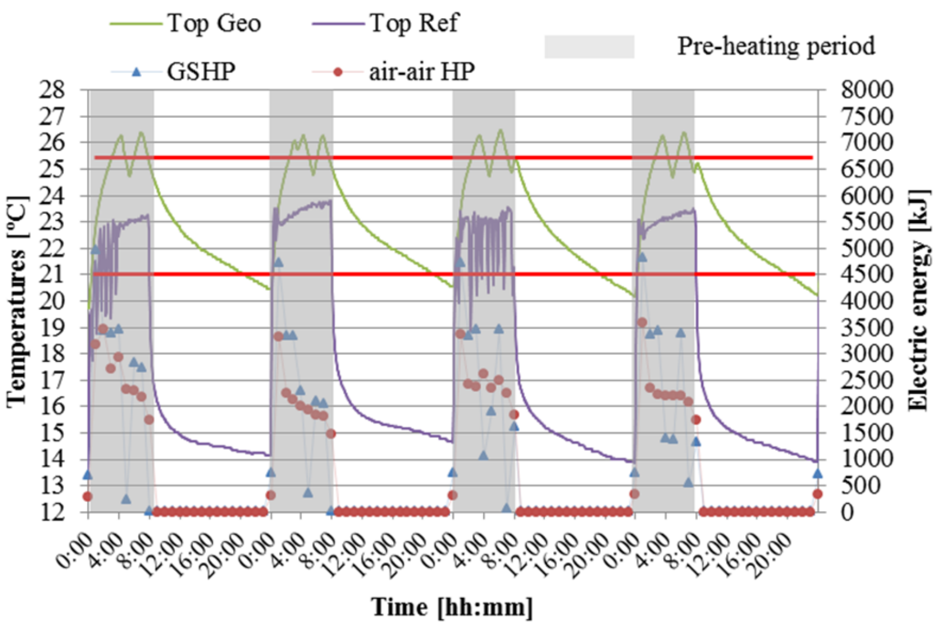

Figure 23. Temperature evolution and hourly energy use in night-time heating test

A further test was carried enhancing the operation strategy of the cubicle. With the requirement of maintaining comfort 24 h, the references were operated continuously, as these could not store heat. On the other side, the radiant cubicle had a pre-heating period at night and a minimum indoor temperature during the rest of the day. The test showed that cost savings were much higher than energy savings, as the radiant wall consumed most of its energy in low cost periods, as shown in Table 10.

Table 10. Energy and cost savings with heating on enhanced operation

	Set-point	Energy savings	Cost savings
Pre-heating 0:00 to 8:00	22 ºC	5.10 %	31.54 %
	24 ºC	15.83 %	39.47 %
Pre-heating 6:00 to 8:00	22 ºC	26.64 %	38.63 %
	24 ºC	35.44 %	46.32 %

8.3 Contribution of the candidate

The candidate was the main responsible on carrying out the experimentation. Furthermore, the candidate also leaded the literature review that was used for planning the experimentation. Finally, the candidate leaded the data analysis and the writing of the paper.

8.4 Journal paper

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Experimental evaluation of a heating radiant wall coupled to a ground source heat pump

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A B S T R A C T

A radiant wall heating system embedded in a heavy brickwork envelope and coupled to a ground source heat pump supplied has been experimentally tested under real outdoor conditions. This system was applied to a room sized cubicle built in Puigverd de Lleida (Spain) test-site, where it was studied in system vs. system analysis in comparison to a reference cubicle built with commercial available technologies (insulated alveolar brick wall and air-to-air heat pump). The results showed the potential of the radiant wall, which in continuous operation reached energy savings between 19.97% and 40.72% based on set-point temperature. Most important, the active thermal mass of radiant wall allowed operating in off peak periods. Otherwise, this peak load shifting ability was completely inexistent in the reference cubicle. However, the results show that the radiant cubicle was unsuited to operate in occupancy schedules due to its slow response time. Furthermore, the tests show that optimization of the radiant wall system requires a control strategy that takes in account the dynamics of the system.

Universitat de Lleida

CHAPTER VIII

Experimental evaluation of a heating radiant wall coupled to a ground source heat pump

J. Romaní, G. Pérez, A. de Gracia, Experimental evaluation of a heating radiant wall coupled to a ground source heat pump. Renewable Energy 105 (2017) 520-529 DOI: 10.1016/j.renene.2016.12.087

9 Development and experimental validation of a transient 2D numeric model for radiant walls

9.1 Introduction

Radiant walls performance, as all TABS, is strongly influenced by the thermal lag. On one side, the interaction with the thermal mass is one of the assets of the radiant wall, as it allows the thermal storage and peak load shifting capabilities [10]. However, this characteristic makes dynamic calculations mandatory for any design and performance study, this is best solved by means of numerical simulations [87].

Finite Volume Models (FVM) were successfully applied to TABS study [40]. This is a robust methodology to simulate heat transfer in building elements. However, as in all simulation methodologies, FVM require simplifications and assumptions. In the case of TABS, a usual assumption is to disregard the heat transfer in the pipes direction, this allows the implementation of symmetry and 2D, which significantly simplifies the discretization and reduces the domain. Furthermore, TABS require definition of convection and radiation heat transfer coefficient, which are usually obtained from correlations and standards.

Finally, any model needs to be validated in order to verify the accuracy and reliability of all the simplifications and assumptions. Consequently, experimental measurements have to be compared to the simulation results.

This chapter presents the development of a numeric model for the radiant wall. The assumptions, the discretization, and the boundary conditions are described. Finally, the model is validated with experimental data and it is later used for a parametric study regarding key design aspects.

9.2 Contribution to state-of-the-art

A transient 2D finite volume model (FVM) of the radiant wall was developed and validated with experimental data. The validation data was obtained from the radiant cubicle after the removal of the ventilated facade, the data set allowed to validate the radiant wall for different orientations of the radiant wall. Once validated, the model was used for a parametrical study of the design variables of the radiant wall and the influence of the control strategy. The results of the research are presented in the following paper:

- J. Romaní, L.F. Cabeza, A. de Gracia, Development and experimental evaluation of a transient 2D numeric model for radiant walls. Submitted to Renewable Energy (June 2017) ref: RENE-D-17-01710

The results of the simulation closely matched the measured results in all the radiant wall orientations, as shown in Figure 24. The average temperature error was below 2 % on the indoor surface, below 13 % on the outdoor surface, and the heat flux error was below 2.4 %, therefore, the model was considered validated.

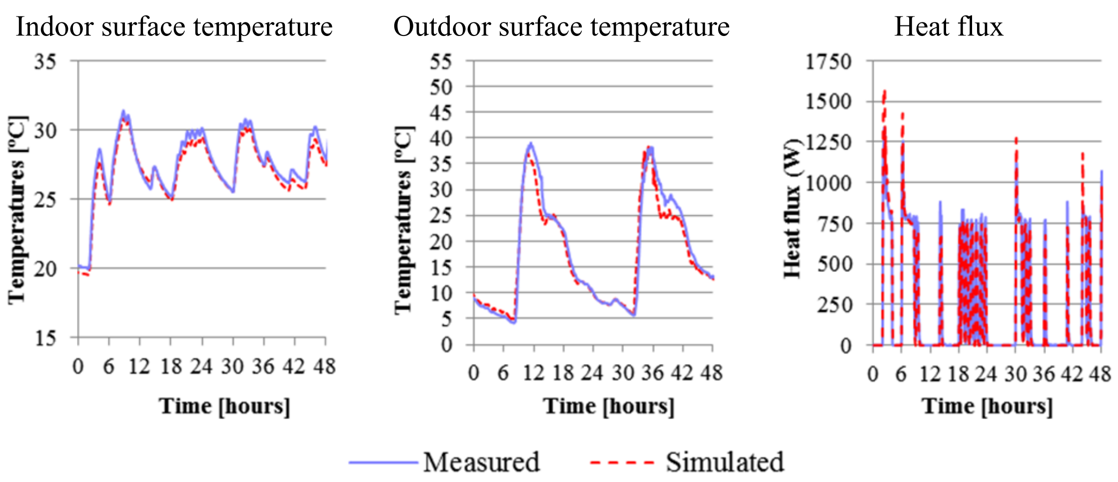

Figure 24. Comparison of the experimental data and simulation results of the East wall

The parametric study was carried out with the objective of maximizing the heat flow and minimizing the temperature gradient on the indoor surface by adjusting the spacing and depth of the pipes. Increasing spacing resulted in higher temperature gradients and lower heat flux per square meter of wall, however, reduced spacing resulted in longer piping, and thus higher pressure losses which can result in higher energy use. On the other side, increasing the depth resulted in a lower temperature gradient on the indoor surface, but heat flow and heat transfer efficiency was reduced. A balance between temperature gradient and heat flow was found in pipes depth between 45 mm and 65 mm and pipes spacing between 125 mm and 150 mm.

Finally, the heat transfer efficiency of the radiant wall depending on the control strategy was studied. Different ON-OFF cycles were used, with periods from 0.5 hours and up to 12 hours, all schedules had a total of 12 ON hours per day. The simulations showed that shorter activation cycles had better heat transfer efficiency, with 0.5 hours schedule having daily transferred heat 20 % higher than 12 hours schedule.

9.3 Contribution of the candidate

The candidate was the main responsible of writing, debugging, and troubleshooting the code of the model. Furthermore, the candidate was in charge of the obtaining and treating the experimental data, as well as being responsible of the development of graphic material of the paper. Finally, the candidate led the writing of the paper.

9.4 Journal paper

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ELSEVIER

Development and experimental validation of a transient 2D numeric model for radiant walls

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An experimental set-up consisting of a house like cubicle exposed to outdoor weather was used to validate a numerical model of a radiant wall. The 2D transient finite volume model used as inputs the indoor temperature, outdoor temperature, global solar radiation incident on a vertical surface, and temperature and flow of the supply water. The simulation results closely agreed with the temperature profiles and heat fluxes for the three studied orientations (East, South, and West). Furthermore, a parametric study was carried out with the radiant wall model, concluding that pipes spacing between 125 mm and 150 mm and depth between 45 mm and 65 mm minimized the temperature difference on the surface while maximizing the heat flux. Furthermore, a control strategy with shorter activation periods improved the heat transfer efficiency.

J. Romaní, L.F. Cabeza, A. de Gracia, Development and experimental evaluation of a transient 2D numeric model for radiant walls. Renewable Energy 115 (2018) 859-870 DOI: 10.1016/j.renene.2017.08.019

10 Control concepts of a radiant wall working as thermal energy storage for peak load shifting with a heat pump coupled to a PV array

10.1 Introduction

The experimental chapters showed the potential of the radiant wall for energy savings. Furthermore, the results highlighted the peak load shifting capability of the radiant wall. In the experimental tests this capability was used to shift energy use to off-peak periods, however, this capability can be used for integrating an intermittent renewable energy source such as the solar energy. Exploiting this concept requires specific controls that charge the wall when the energy is available.

A layout for achieving net-zero energy buildings consists in using a TES supplied by a heat pump coupled to a PV array. However, most studies in the topic fulfil the goal by using the grid as electricity energy storage [98], and thus by continuously importing and exporting energy. Furthermore, few studies considered TABS as TES [33], additionally, it was never treated as standalone storage.

The previous chapter presented the validation of a numeric model of the radiant wall. This model was useful for studying the design parameters and the behaviour of the system. However, an in deep study of the control for the radiant wall requires a model that generates a cooling or heating demand, and thus, a model in which the indoor temperature is an independent variable. Consequently, the model of the radiant wall needed to be coupled to a building or room model in order to study different control strategies.

This chapter presents the process followed to link the radiant wall model to a full room model. This room model was coupled to heat pump and PV array model in order to study different control concepts that exploited the peak load shifting capability of the radiant wall.

10.2 Contribution to state-of-the-art

The chapter first presents the model used in the study, which consist in a room with six surface linked together through the methodology proposed by Seem [99]. The surfaces consisted in the floor, the ceiling, and four radiant walls. The models of the first two are presented together with the modifications of the radiant wall model in order to fit boundary conditions of the room model. This room model was used to study different control concepts to accomplish one or more of the following objectives: to maximize the use of the energy produced by the PV panels, to minimize imported energy from the grid, to minimize imported energy from the grid in peak periods, and to shift energy use to off-peak periods. The imported energy from the grid was considered as the electricity used by the heat pump that was supplied by the electric grid, and thus the energy that was not supplied by the PV panels. The results of this study were presented in the following research paper:

- J. Romaní, M. Belusko, A. Alemu, L.F. Cabeza, A. de Gracia, F. Bruno, Control concepts of radiant wall as thermal energy storage for peak load shifting with a heat pump coupled to a PV array, Submitted to Renewable Energy (July 2017) RENE-D-17-02177

The control concepts were divided into three main groups: “no-control”, “solar”, and “peak load shifting”. The “no-control” concept focused on just maintaining the comfort range, preventing the room to exceed 26 ºC. “Solar” concepts focused in exploiting the production of the PV panels, by charging the radiant wall during daylight time by lowering the set-point to 22 ºC. The “solar” concept was divided into several types. “Solar basic” simply lowered the set-point during daylight hours without taking into account any other parameters. Next concept was “solar following”, in which the charging only occurred if PV output exceeded 1500 W. “Solar hybrid” was a mixed approach between the two previous, charging freely during off-peak periods with daylight, but only charging in peak periods if the PV output was enough. The last solar concept was “solar predictive”, which worked as “solar following” but adding a pre-cooling period in the night. The set-point in this pre-cooling period depended of the predicted solar radiation. Finally, "peak load shifting" concepts charged the radiant walls during night off-peak hours.

Figure 25 shows that "solar" control concepts used more energy, as the cooling load was higher due to longer periods at low set-point. However, once considering self-consumption of the energy produced by the PV panels, "solar" concepts had the lowest imported energy. Among them, "hybrid" concept had both the less imported energy and the less peak energy used in the set-up used. However, the results suggest that with more PV installed capacity "following" concept would guarantee no imported energy.

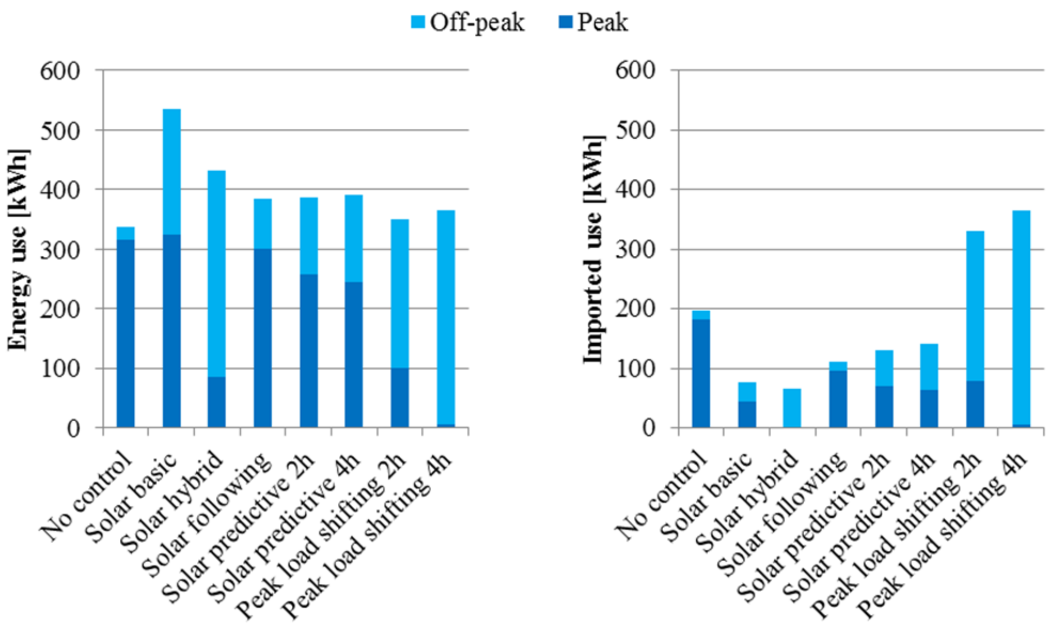

Figure 25. Total peak and total off-peak energy use (left) and imported energy (right) (all summer)

Regarding the operation cost, the results reflect the energy use of each concept, with "hybrid" concept having the lowest operation cost, as shown in Figure 26. On the other side, "no-control" + PV gave no economic benefit compared to "peak load shifting" concepts without PV. Consequently, the investment on PV panels would only be fully exploited with "solar" control concepts.

The results also pointed to many parameters that could be optimized in the control of the system. The more significant were set-point temperatures in charging modes, length and timing of the charging periods, PV output threshold for activating the heat pump, and definition of the predictive criteria.

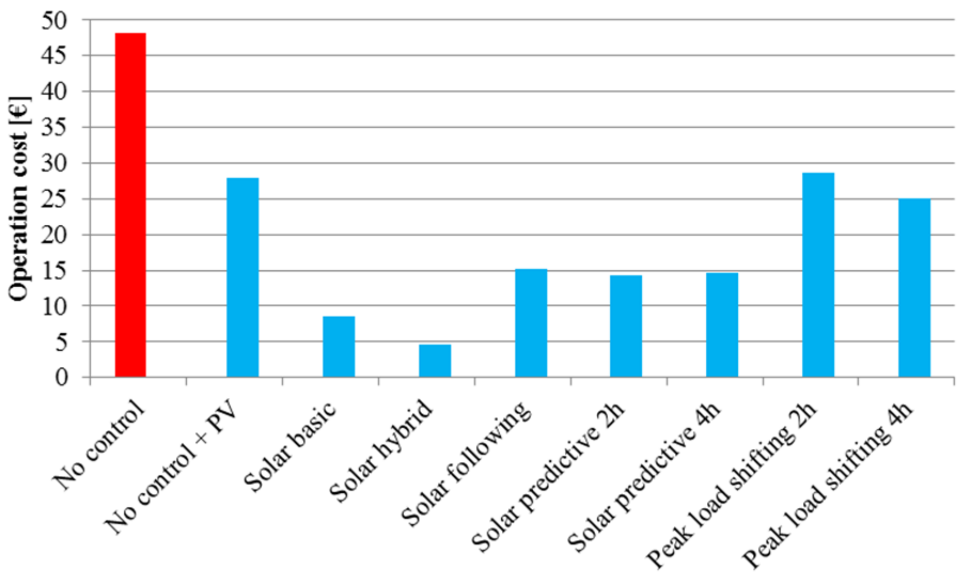

Figure 26. Operation cost of each control concepts (all "solar" concepts consider self-consumption of PV energy)

10.3 Contribution of the candidate

The candidate was in charge of developing the room model according the methodology and know-how of UNISA co-authors. This implied writing, debugging, troubleshooting, and verification of the model. Then, the control concepts were defined through a discussion between all co-authors. Finally, the candidate was in charge of carrying out the simulation, treating the data, generating the graphic material, and leading the writing of the paper.

10.4 Journal paper

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Control concepts of a radiant wall working as thermal energy storage for peak load shifting of a heat pump coupled to a PV array

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Photovoltaic panels (PV) coupled to a heat pump supplying heat to a radiant wall is a system with potential to reduce the imported energy from the grid for heating and cooling of buildings. The radiant wall works as a thermal storage system (TES) allowing storage of the PV output and, thus, peak load shifting. However, the management of these technologies is complex due to the dynamics of the system. This paper presents several control concepts with different purposes such as shifting energy use to off-peak periods, maximizing self-consumption of PV output, and minimization of imported energy from the grid. An experimentally validated numerical model from previous research was used to investigate and compare the different proposed control concepts. Results showed that charging the wall with solar energy resulted in higher overall energy use of the heat pump, while the imported grid energy was significantly reduced, thanks to self-consumption.

J. Romaní, M. Belusko, A. Alemu, L.F. Cabeza, A. de Gracia, F. Bruno, Control concepts of radiant wall as thermal energy storage for peak load shifting with a heat pump coupled to a PV array. Renewable Energy 118 (2018) 489-501 DOI: 10.1016/j.renene.2017.11.036

11 Conclusions and recommendations for further work

11.1 Conclusions

This thesis studied the capabilities and potential of a radiant wall. The experimental set-up provided three years of measured data, which resulted in a deep knowledge of the behaviour of the system in different conditions. Additionally, the experimental data was the base for a reliable simulation study, which involved the development and validation of a model for the radiant wall and the study of different control concepts. The conclusions are divided into the specific conclusions of each of the papers and the general conclusions of the thesis.

11.1.1 General conclusions

The results of this thesis showed that the radiant wall is a useful technology for achieving the goal of net-zero energy buildings. The main conclusions are:

- Radiant walls are part of the less developed type of TABS, moreover, until now most of the research consisted in simulation and laboratory studies. However, radiant walls present interesting characteristics, such as good performance for both heating and cooling purpose or capability for reducing the influence of outdoor conditions.
- The radiant wall has potential for reduction of the energy use for both heating and cooling of building through the integration of renewable energies such as ground source heat pumps, ground heat exchangers, or PV panels, among others.
- The performance of the radiant wall is very sensitive to certain operation parameters. Well defined control strategies are the key to better exploit the energy and cost savings potential of the radiant wall.
- A finite volume model of the radiant wall was validated with experimental data from a set-up under outdoor conditions. The model proved its utility for studying the design parameters of the radiant wall.

11.1.2 Specific conclusions

The state-of-the-art of TABS technology was reflected in a review. In this, the general characteristics were described, together with summary of the different terminology used. However, the main focus was on the simulation tools and the control strategies applied in this technology. The main findings can be summarized as follows:

- TABS are promising technologies for reducing the energy use in the building sector. The main challenges are the dimensioning, design and the development of efficient controls.
- Many types of simulation models were applied to research, design, and control of TABS. Some examples come from simple analytic and semi-analytic models, to detailed numeric models, and up to simplified models using statistical identification techniques. Modelling of TABS emphasized the necessity of transient models that take into account the dynamic behaviour of the system.
- Control of TABS implied determining the supply temperature, the ON/OFF criterion and the change between heating and cooling modes. Set-back controls and heating/cooling curves are simple and robust controls, however, optimization of TABS and integration of renewable energies required more advanced controls.
- The literature showed the great energy savings potential and CO_2 emission reduction that can be achieved with TABS. Still, the technology required further research to encourage its application to buildings refurbishment and to improve coordination of TABS with ventilation, and management of heat gains.

The summer experimentation of the radiant cubicle in free-cooling mode led to the following conclusions:

- The radiant wall coupled to a ground heat exchanger showed good energy savings in the Puigverd de Lleida test site. However, the savings were very sensitive to the indoor set-point, as the ground temperature of 17 – 18 ºC limited the supply temperature.

- 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.
- Operation on occupancy schedules limited the performance of the radiant wall. While the reference cubicle reduced its operation time, and thus its energy use, the low response time of the radiant wall resulted in proportion longer operation times. In these schedules the radiant wall did not exploit it peak load shifting capacity.
- 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.

The knowledge acquired during with the experimentation of the radiant wall cubicle in free-cooling mode was later complemented with the study of the effect of internal loads. The main conclusions of this research are summarized as follows:

- The ground heat exchanger limited the cooling power of the system, as the supply temperature could not be regulated. Despite the test were carried out with internal gains equivalent to a high energy intensive building, the radiant wall coupled to the ground heat exchanger could maintain the indoor temperature in the comfort range. However, a low energy building will better exploit the potentiality of the free-cooling.

- The average thermal power and overall efficiency of the system could be improved by intermittent operation. With a cyclic operation the temperature between the boreholes and the radiant wall increased, and thus the heat transfer improved.
- The radiant wall showed its capability for energy storage even under hot weather conditions and intense internal gains. Under occupancy scheduled internal gains the system achieved operation cost savings despite having a higher energy use than the reference. This was achieved through peak load shifting to off-peak periods.

The experimental research was completed with winter tests, in which the radiant cubicle was heated by a ground source heat pump. The main conclusions of this research were:

- The radiant wall cubicle coupled to a ground source heat pump showed good savings potential in all the tested conditions. Despite this, the energy savings were dependent of the set-point temperatures and the operation schedules.
- The tests showed that the radiant wall could also exploit its peak load shifting capability in winter conditions. Using night pre-heating periods the radiant cubicle achieved further operation cost savings than energy savings.
- Pre-heating during night-time increased heat loss in certain cases, especially in long pre-heating periods, which required repeated reheat cycles to maintain the set-point temperature. This highlighted the importance of and advanced control that could predict the required heat pulse that achieved the set-point temperature at the adequate time.

The transition between experimentation and simulation was developed in a model validation study. This presented a numeric model of the radiant wall which was validated with experimental data. Then, the model was used for a parametric study that led to the following conclusions:

- The 2D transient FVM of the radiant wall showed its validity through good agreement with the experimental data of three different orientations. The match between simulated values and experimental data proved that the assumptions were reasonable and representative of the system.
- Assuming that the fluid at constant average temperature between inlet and outlet was checked, showing little error and good agreement to heat flux values. Consequently, the key simplifications derived from this assumption, 2D and symmetry, were acceptable.
- The spacing and depth of the embedded pipes in the radiant wall are parameters that strongly influence to the performance. The parametric study suggested that spacing between 125 mm and 150 mm and depth between 45 mm and 65 mm maximized the heat flux and minimized the temperature difference on the indoor surface, which are two of the main reference values to the radiant wall performance.
- The low conductivity of the radiant wall caused a temperature increase during the active periods, and thus the heat transfer efficiency progressively decreased. Cyclic activation in shorter periods avoided this temperature increase, resulting in a better heat transfer.

Finally, the validated model was used to study a systems consisting of radiant walls working as the TES for a heat pump coupled to a PV array. Different control concepts were used in order to find the best strategy to exploit the energy produced by the PV. The results of this research are summarized in the following conclusions:

- Considering the radiant wall as a TES system for the PV production resulted in a higher energy use of the heat pump. However, as most of the energy consumed came from the PV panels, the imported energy and the operation cost were very low.
- The studied control concepts pointed to many parameters that could optimize the operation of the system. The most important were: indoor temperature set-point,

PV output threshold for activating the heat pump, and forecasting of the PV production, the expected cooling load and the length and timing of charging periods.

- Investment in a PV array was only justified under control strategies that maximized the self-consumption. In these cases, the operation costs for cooling were very low.

11.2 Recommendations for further work

11.2.1 General remarks

The research of this thesis gathered a huge amount of experimental data of the radiant wall cubicle. The analysis of this data showed the potential of this technology for reducing the energy use of buildings through the integration of renewable energies. The results clearly pointed to the radiant walls, and by extension TABS, as a candidate for achieving the goals towards net-zero energy buildings.

However, the radiant wall used in the experimental set-up did not have an optimized design. Moreover, the radiant wall construction process was neither economically feasible nor sustainable. Consequently, further research is undoubtedly needed to make the radiant wall a competitive commercial system.

On the other side, the thesis opened a research path into simulation through the validation of a model of the radiant wall. A first step in this area was taken, by integrating the radiant wall model to a room model and studying some control concepts. However, the options offered by the simulation are huge, and this can be the key to develop the system to a mature state.

Consequently, several recommendations for further work arise at short and long therm.

11.2.2 Further work at short term

The used experimental set-up is versatile and different kind of tests can be performed, while this thesis covered some of the more relevant research topics there are still areas to be researched. Some suggestions for experimentation are listed:

- The internal gains increase the cooling load in summer, but reduce the heating load in winter. As the radiant wall is more sensitive to the heating load than the reference, a study of the effect of internal gains to heating performance would provide valuable information.
- The tests carried out used all the five radiant walls loops of the cubicle together, and thus the radiant surface per square meter of the indoor space was very high. This set-up is unrealistic, as in a real building the vertical surfaces have openings and coverings that would not allow installing radiant wall everywhere. Furthermore, reducing the radiant wall surface will also reduce the installation cost. As a result, research around the necessary radiant wall surface for cooling or heating a building would be interesting.
- The experimental set-up provides a house-like cubicle that is exposed to outdoor conditions, yet the test conditions can be monitored globally. This set-up would be useful for demonstration of advanced controls, in a controlled environment that is yet representative of the boundary conditions of a building.

Regarding the simulation, the research done presented few points that can be further studied with the current models. Moreover, those can be used for further research on topics which were not considered in the current thesis:

- The concept of the radiant wall as TES storage for a heat pump coupled to a PV array can also be applied to winter. More interestingly, the characteristics of the heating seasons require of different control concepts than in cooling.

- The study of the control concepts presented many parameters that could be improved. Optimization of these parameters in different scenarios will lead to a better knowledge of the required control strategy for the radiant wall.
- The simulation only considered an air-to-water heat pump, however, as shown in the experimental part and in the literature review, many different supply systems can be applied. The study of the radiant wall coupled to these energy sources could provide interesting knowledge of which system is the most suitable to different climates.

11.2.3 Recommendations for further work at long term

Beyond the complementary work to this thesis, the development of the radiant wall requires steps that take it further into commercialisation.

- The huge amount of data gathered in the test site is a valuable resource that is strongly needed in one of the research trends in buildings: model identification. Many techniques have been developed in the statistical identification of models, however, the main issue for their implementation is the lack of data to test them. These models are key to some advanced control strategies, and thus, applying the obtained experimental data to the development of identification models could be a great step forward for these techniques.
- The radiant wall showed a great potential compared to conventional system, however, the other TABS layouts, mainly radiant floors and ceilings, present operation advantages in heating and cooling modes, respectively. A thorough study comparing these three systems in a full building model would help to determine which building types and climatic areas benefit the most from each layout.
- In contrast to radiant ceiling and radiant floors, the radiant wall does not have a commercial available system for its constructions. Obviously, a key milestone in the implementation of the radiant wall is the design of a feasible method for installing radiant walls. This should consider new-built building, without

disregarding refurbishment. A key to the success in the design must be the life cycle analysis of the building, which proves that the overall performance of the building is sustainable beyond doubt.

12 Other research activities

12.1 Other publications

A contribution to one paper was carried out during the development of this thesis:

- A. de Gracia, L. Navarro, J. Coma, S. Serrano, J. Romaní, G. Pérez, L.F. Cabeza, Experimental set-up for testing active and passive systems for energy savings in buildings - Lessons learnt. Submitted to Renewable Energy Reviews (May 2017) ref: RSER-D-17-01202

12.2 Conference contributions

Three conference contributions were presented orally during the thesis:

- J. Romaní, L.F. Cabeza, A. de Gracia, Experimental evaluation of a cooling radiant wall coupled to a ground heat exchanger. INNOSTORAGE Conference – Beer-Sheva (Israel), February 16th to 18th, 2016
- J. Gasia, J. Romaní, L.F. Cabeza, Subtask 5: KPI definitions. ECES IA-IEA Annex 30 Workshop, Tokyo (Japan), October 17th to 19th 2016
- J. Romaní, A. de Gracia, L.F. Cabeza, G. Pérez, Radiant wall potential and effect on radiant asymmetry. 10th Thermodynamic Engineering International Conference (CNIT), Lleida (Spain), June 28th to 30th 2017

Other three conference contributions were done:

- J. Gasia, J. Romani, L.F. Cabeza, Subtask 3- Key performance indicators (KPI) for thermal energy storage (TES). ECES IA-IEA Annex 30 - Second meeting, Frankfurt (Germany), May 2nd to 3rd 2016
- J. Gasia, J. Romani, G. Peiró, L. Miró, C. Prieto, L.F. Cabeza, High temperature TES pilot plant: Experimental research and lessons learnt. ECES IA-IEA Annex 30 Workshop, Tokyo (Japan), October 17th to 19th 2016

- J. Gasia, J. Romani, G. Peiró, L. Miró, C. Prieto, L.F. Cabeza, Operation characteristics of molten salts for CSP plants. ECES IA-IEA Annex 30 Workshop, Tokyo (Japan), October 17th to 19th 2016

12.3 Scientific foreign exchange at University of South Australia (Adelaide, Australia)

The development of the thesis involved a foreign exchange at Barbara Hardy institute, a research group from the University of South Australia (UNISA). The exchange was possible thank to researchers mobility project INNOSTORAGE.

University of South Australia

Under the supervision of Dr. Martin Belusko and with the close cooperation with Dr. Alemu Alemu, the candidate integrated the radiant wall model to the simulation of a full room. This was the starting point for investigating different control strategies for implementing the system consisting in the radiant wall as TES for a heat pump coupled to a PV array.

12.4 Projects participation

- Nuevo cerramiento para la mejora de la eficiencia energética en edificación basado en integración geotérmica. EEA Grants, Nº IDI-20140914 (2014-2015)
- More effective use of renewables including compact seasonal thermal energy storage. European Commission Seventh Framework Programme (FP/2007-2013), Nº ENER/FP7/295983 (MERITS), 2012-2016
- Identificación de barreras y oportunidades sostenibles en los materiales y aplicaciones del almacenamiento de energía térmica. Ministerio de economía,

industria y competitividad ENE2015-64117-C5-1-R (MINECO/FEDER), 2016-2018.

- Use of innovative thermal energy storage for marked energy savings and significant lowering of CO2 emissions (INNOSTORAGE). European Commission Seventh Framework Programme (FP/2007-2013), Nº PIRSES-GA-2013-610692, 2013-2017.
- PhD on Innovation Pathways for TES (INPATH-TES), European Union's Horizon 2020 research and innovation programme, Nº 657466, 2015-2018.
- Grup de recerca en energia en maquinària agroindustrial. AGAUR, Modalitat grup de recerca consolidat Nº 2014 SGR 123, 2014-2016

12.5 Experts network participation

- Annex 30: Thermal energy storage for cost-effective energy management and CO_2 mitigation. International Energy Agency implementing agreement Energy Conservation through Energy Storage (ECES).

Universitat de Lleida

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