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

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ABSTRACT

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.

1. Introduction

In the last decades, there has been much concern on the energy consumption and greenhouse gases emissions, which led to COP21 agreement [1] establishing the objective of maintaining the global average temperature increase below 2 °C above pre-industrial levels, but pursuing efforts to not reach an increase higher than 1.5 °C. Related to this point, on 2012 the International Energy Agency (IEA) [2] calculated that buildings account for 32% of global energy use and almost 10% of total direct energy-related CO_2 emissions. If electricity generation and district heating emissions are taken into account, then buildings are responsible for over 30% of total end-use energy-related CO_2 emissions. Consequently legislations and regulations were issued to tackle this problem, as an example the European Directive 2010/31/EU [3] stands that by 2020 new buildings must be designed to consume “nearly zero” energy and existing buildings must be refurbished into very low energy buildings.

A promising technology for energy reduction in buildings is the thermally activated building systems (TABS). TABS are pipes or ducts embedded in the building surfaces or structures to work as heat exchangers, which provide heating and/or cooling to the rooms and store heat in the thermal mass of building components. These activated surfaces mainly exchange heat with the room in form of radiation, that means that TABS also directly exchange heat with the occupants. This characteristic implies both comfort and energy advantages. On the comfort side, heating and cooling with TABS reduces the required air change rate to the minimum for ventilation. Consequently, this reduces draught and noises. On the energy side, TABS can achieve operative temperatures inside the comfort range with variable air temperature, consequently reducing ventilation energy loses as indoor air has a temperature nearer to outdoor air temperature. However, the main point is that TABS make use of the buildings large surfaces, hence they can achieve high heat flux even with low temperature gradients. As a result TABS allow operation with high temperature cooling and low temperature heating. Furthermore, this low temperature gradient improves chillers and boilers performance, moreover, it makes the use of low grade energy sources feasible. Finally, TABS make and active use of the building thermal mass, which can be used for peak load shifting thus profiting of low cost energy periods and reinforcing the use of environmental energy sources available in short periods [4].

The benefits of peak load shifting have been studied for different TABS applications. In order to minimize cooling with a heat pump,

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Nomenclature

TABS	Thermally Activated Building Systems
VTABS	Vertical Thermally Activated Building Systems
TB	Thermal Barrier
HP	Heat Pump
GSHP	Ground Source Heat Pump
AAHP	Air to Air Heat Pump
COP	Coefficient of Performance
Top Geo	Operative temperature of geothermal cubicle
Top Ref	Operative temperature of reference cubicle
Tout	Outdoor ambient temperature
UBB	Unknown But Bounded
GSC	Gain Scheduling Control
PWM	Pulse Width Modulation
MPC	Model Predictive Control

Meierhans studied radiant cooling applied to an office building [5,6]. The ceiling slabs shifted the cooling load to night-time when free-cooling was available as outdoor cool air. The monitoring of a room showed that the system could maintain comfort temperature even with internal and solar heat gains. Similar conclusions were obtained by Olesen et al. [7], whose dynamic simulations pointed that TABS could help in reducing and shifting operation time by night-time activation or intermittent operation of the supply pumps, all without losing comfort. On that point, Bauman et al. [8] compared the operation schedules of monitored radiant slab office buildings. First, using a schedule typical to quick response all-air system and then contrasting it with a night-time pre-cooling schedule. The comparison showed that the radiant slab could successfully maintain comfort conditions. Furthermore, comfort surveys showed a good occupant satisfaction. The benefits of peak load shifting extend also to supply systems. On this point dynamic simulations by Dossi et al. [9] showed that night-time heat storage helped reducing peak load, which improved heat-pumps COP. Furthermore, TABS were also useful to reduce operation cost, as operation could be shifted to low cost periods. On that point, Sarbu and Sebarchievici [10] showed that a radiant floor required less on/off switching than a radiator, which reduces the stress on the heat pump equipment, thus it required less maintenance and it had a longer life time.

The TABS high thermal mass that makes possible to shift peak loads also makes their control challenging. In that sense, heating curve and indoor temperature feedback have been standard in TABS control strategies. However, control strategies have been improved with better definition of heating and cooling curves in form of Unknown But Bounded method (UBB) [11,12] and techniques to define the active periods such as the improvement of PID through Gain Scheduling Control (GSC) [13,14], the calculation of the heat pulse with Pulse Width Modulation (PWM) [15,16], the use of statistically identified model in Model Predictive Control (MPC) [17,18] or with the development of adaptive and predictive controls [19,20].

Most of TABS that have been researched and applied to buildings were placed on horizontal surfaces, such as floors, ceiling, and in-floor slabs. However, TABS can be also placed in vertical surfaces with panels or embedded into walls. In one of these cases, Zhu et al. [21] studied pipe-embedded envelopes. This type of TABS is placed on outer walls and in that specific case the supplied water was used for intercepting the heat waves from outdoor ambient and, consequently, reducing cooling and heating demand. The heat sources and sinks were cooling towers and ground heat exchangers for cooling or solar collectors and ground heat storage for heating. The results of the study showed that pipe-embedded envelopes actively intercepted heat/cold and reduced the cooling/heating load of the building. The model developed in this study, a 2D model Frequency Domain Finite Difference (FDFD) was further used for a parametric study [22]. Later, the model was improved with genetic algorithm for defining the model parameter [23], afterwards it was coupled to the Number of Transfer Units (NTU) method for considering the temperature variation in the pipe direction [24]. Krzaczek and Kowalczuk [13] applied the same concept, in this case called Thermal Barriers (TB), but coupled to heat storage system consisting of ideal ground heat sources divided in three levels: low temperature, medium temperature, and high temperature heated with solar collectors. The results also showed the capacity of the TB for reducing the heating and cooling demand of the building. In this study a Finite Elements Model (FEM) was developed and used for a parametric study of the TB. The research continued with the development of a Fuzzy Mixing Gain Scheduling (FMGS) controller for TB [14]. Complementary, the components and structure of the TB were studied [25]. Also in a simulation study, Bojic [26] used EnergyPlus to show the better synergy of radiant panels with the building insulation compared to conventional radiators. Aside from simulation research, Venko et al. [27] made a laboratory experimental study. The focus was on the convective part of the radiant panels, studying the activation length of vertical TABS on mixed convection conditions.

As previously stated, the use of TABS can enhance the use of renewables. In this context low enthalpy geothermal systems combined with heat pumps have been commonly coupled to TABS. Ground Source Heat Pumps (GSHP), also called Geothermal Heat Pumps, are systems combining heat pumps with a ground heat exchanger (closed loop systems) or fed by groundwater from a well (open loop systems) [28]. These systems use the constant temperature of the ground, whose thermal capacitance reduces the daily and seasonal temperature fluctuation as the depth increases [29]. The ground temperature stays around the yearly average outdoor temperature, consequently being higher than the average outdoor temperature in winter and lower in summer. As a result, using the ground as heat source or heat sink increases the efficiency of heat pumps (HP) both in heating and cooling modes. The performance of HP can be further improved with TABS because they require a supply temperature lower for heating or higher for cooling, therefore GSHP coupled to TABS benefit from a reduced temperature difference between the evaporator and the condenser.

Despite many research has been conducted both on TABS and GSHP, there are no examples that integrate both a VTABS and GSHP in pilot plan experimentation. Furthermore, most VTABS research has been done in simulations works or at laboratory tests. Consequently, testing of VTABS under real outdoor conditions is valuable for obtaining information to evaluate the potential of such systems and to validate simulation models with real data.

In this context, the present paper describes the experimentation under real outdoor conditions in a house-like prototype scale. The study was based on system vs. system comparison, the cubicles built allowed for a comparative study of buildings with equivalent envelopes but using different HVAC systems and distribution system, in that case a radiant wall coupled to a GSHP on a side and a conventional air-to-air heat pump on the other. The studied radiant wall differs from other VTABS found on the literature, as most radiant systems are embedded into concrete [13,23] or made of radiant panels [26,27] while the cubicle built for this study had the radiant system embedded into a heavy brick wall. The present experimental study pretends to demonstrate the energy savings potential of the system as well as its peak load shifting ability.