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Analysis of control strategies for thermally activated building systems under demand side management mechanisms

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ABSTRACT

Thermally activated buildings systems (TABS) are systems that integrate heating/cooling devices in the building structure, so that the building elements act as thermal storage and have an active role in the energy supply and demand management. Although TABS are well known systems, there are still open questions in their realization, mainly concerning appropriate control strategies which are influenced by the large thermal inertia. The purpose of this paper is to analyze the influence of demand side management control strategies on the performance of a thermally activated building system applied in a commercial building. The goal is to estimate the potential of TABS for load shifting requested by the electricity grid. The analysis is performed by means of a sample case: first the existing TABS control strategy and then the possible implementation of DSM mechanisms are analyzed. In particular three different demand side management mechanisms are evaluated: (i) a peak shaving strategy, (ii) a random request of switching on/off the system and (iii) a night load shifting strategy. The simulation results show high potential of TABS within the DSM framework, since TABS allow load control while scarcely affect thermal comfort.

1. Introduction

Thermally activated buildings systems (TABS) are systems that integrate heating/cooling devices in the building structure, so that the building elements act as thermal storage and have an active role in the energy supply and demand management. They are typically realized by means of pipes embedded in concrete slabs (floors, ceilings, walls) with water as heat transfer medium. Main advantages of these systems are: they allow for demand peak shaving and consequently for reduction of heating/cooling capacity; energy demand and supply can be shifted thanks to mass thermal buffer; the large thermo-active surfaces allow small temperature differences between room and structure and low temperature heating and high temperature cooling sources [1].

Although TABS are well known systems and recognized as energy efficient and economically viable, there are still open questions in their realization, mainly concerning the control strategy. The control strategy is influenced by the large thermal inertia of TABS, it has to comply with different comfort requirements in different rooms within the same hydraulic circuit and it has to be designed for year-round operation and to avoid frequent switching between heating and cooling mode [2]. TABS have a self-controlling effect, meaning that they could be supplied with constant water temperature (e.g. 22 °C all the year-round) and be able to achieve thermal comfort, providing both heating and cooling, when there is a small temperature difference between the water temperature and the room air temperature. This strategy is not effective for high heat gains and large temperature fluctuations [3]. Gwerder et al. [2] listed typical features of TABS control solutions: (i) they use water flow temperature compensated on the basis of the outside temperature (the temperature set point of the water flow is shifted with varying outside temperature according to the heating curve); (ii) they do not employ feedback signals from the TABS zones; (iii) heating or cooling mode depends on the season and/or on the outside temperature.

Generally these systems are operated continuously with a constant flow rate, but also intermittent operation has been evaluated. Gwerder et al. [4] showed that with a pulse width modulation control (PWM), which operates the TABS zone pump in an intermittent way, energy savings are obtained and operation periods of the plant can be shifted to times with high energy generation efficiency. Due to the large thermal inertia of TABS, instant correction of the room temperature cannot be achieved, however day-to-day room temperature compensation is promising [4]. Furthermore,

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Fig. 1. Representation of TABS used in the reference building (Airdeck).

Sourbron et al. [5] demonstrated that room temperature feedback control strategies can be inadequate for TABS because they cause frequent switching between heating and cooling with a dramatic impact on the energy performance. De Wit and Wisse [3] stated that the operating mode can be controlled by the room air temperature if a dead band is applied between the air temperature set point for the heating mode and the air temperature set point for the cooling mode, so that the system is more stable. It is possible to control different rooms with different comfort requirements by dividing the building into several zones with similar features and control each zone separately. Not only the division in zones, but also the hydraulic circuit topology has a paramount importance on the operating conditions and energy demand of TABS [1,3].

In order to determine the water supply temperature the UBB (unknown-but-bounded) approach has been proposed by Gwerder et al. [2]. It takes into account the dynamic behaviour of the system and the influence of internal and external gains on the heating and cooling loads. Such gains have an important role for the achievement of the required indoor thermal comfort, as demonstrated by Saelens et al. [6], who analyzed the energy and comfort performance of TABS under different occupant behaviour. Kolarik et al. [7] showed that the application of the TABS decreases the primary energy use in comparison with traditional systems without a significant decrement of occupants' performance. Moreover another recent topic of research about TABS concerns the positive role of model predictive control to increase their energy efficiency [8,9].

The purpose of this paper is to examine in depth TABS control strategies and their potential for load shifting on demand. In particular the aim is to analyze, by means of a sample case, the influence of demand side management (DSM) mechanisms on the performance of a thermally activated commercial building.

All strategies intended to influence the customer's use of energy are considered demand-side management and can be used to reduce customer demand at peak times, reduce energy consumption seasonally or yearly, change the timing of end-use consumption from high-cost periods to low-cost periods and increase consumption during off-peak periods [10]. DSM programs can have a benefit both for customers and utility. From the customer point of view, they can allow cost benefits for lower electricity bills and this is strongly influenced by a price responsive demand which is deemed fundamental for the demand-side management concept [11]. From the utility perspective proper DSM mechanisms help to make more efficient use of the existing generating capacity and can reduce the need for new capacity. TABS with their high thermal mass behave like a thermal storage so they have an undeniable potential to shift loads on the basis of external requests [12]. This paper aims at analyzing their behaviour and assessing their potential as DSM instruments.

2. Methods

The analysis is performed by means of a sample case, represented and simulated with a dynamic simulation tool (TRNSYS [13]). The study of this commercial building was part of the activities of the GEOTABS project [14]. In this paper first the performance of a conventional TABS control strategy is investigated, then the possible implementation of DSM mechanisms are analyzed by means of sensitivity analysis and multi-objective optimization. As far as the conventional control strategy is concerned, the influence of the supply water temperature on the building performance is evaluated, in order to understand the robustness of the system as it is. Second, the TABS behaviour under three different demand side management mechanisms is assessed: (i) a peak shaving strategy (DSM1), (ii) a random request of switching on/off the system (DSM2) and (iii) a night load shifting strategy (DSM3).

2.1. The sample case

The reference building is named Hollandsch Huys, it is located in Belgium. The building total floor area is 4500 m^2 which are currently partially occupied. The building is well insulated (external walls *U*-value 0.21 $W/m^2 K$) and triple glazing is adopted (*U*-value of 0.65 $W/m^2 K$ and *g*-value of 0.5). The building has four floors with different schemes of TABS integration with additional HVAC systems. The concrete slabs of Hollandsch Huys, which act as TABS, are built around voids (Fig. 1) of 0.24 m height and average 0.20 m side, with distance between the centres of adjacent air boxes of 0.30 m. Pipes have outer diameter of 0.02 m, and are spaced horizontally in two layers, following the layout of voids, i.e. 0.30 m between pipes. A dynamic slat shading system is provided, it is lowered when the total irradiation on the façade exceeds 250 W/m^2, while it is raised again when the irradiation falls below 150 W/m^2. The slat inclination angle depends on the solar altitude. The heating, ventilation and air condition (HVAC) system comprises an air handling unit (AHU) and the production unit (a ground coupled heat pump). The AHU is dedicated to maintain the indoor air quality based on CO_2 level. Heating and cooling of fresh air is done using water provided by the production unit, and a backup boiler is available in case the heat pump heating capacity is not enough. The heat pump has a nominal cooling/heating capacity of 142 kW and 181 kW, respectively. The heat pump is connected to the building and to the ground by a number of heat exchangers, storages and pumps. The geothermal system comprises 2 linear bore fields of 14 and 8 U-tube ground heat exchangers (GHX) with a 75 m depth and 5 m spacing in between. The pipes are made of PE 100 and have an external pipe diameter of 0.032 m and a shell thickness of 0.003 m.

The production plant can work in heating mode, active cooling mode or passive cooling mode. In the latter the cold is extracted from the ground through direct heat exchange between the brine