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Efficiently produced heat and cold is squandered by inappropriate control strategies: A case study

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ABSTRACT

The large thermal time constant of thermally activated building systems (TABS) hampers communication between the system's production and emission. Therefore, conventional building control strategies, typically using room temperature feedback, are unadapted to control thermal comfort efficiently. In this paper, measurement data and simulation results reveal that unadapted TABS control has a dramatic impact on overall energy performance. Measurements in a TABS building with room temperature feedback show the HVAC system switching between heating and cooling in a very short time frame. A simplified, generic room model is used to simulate, understand and evaluate this behaviour. For room temperature feedback control, only 45% of the cold and 15% of the heat produced actually controls room temperature. The remainder is stored in the TABS and exchanged between the heating and cooling system. Enlarging the heating-to-cooling set point band improves this ratio, while maintaining thermal comfort. On the other hand, night time operation control of the circulation pump, adapted to the TABS thermal time constant, eliminates this 'unused' energy completely. In this case, however, even with perfect heat gain forecasts, it is difficult to avoid room temperatures dropping below thermal comfort limits during initial office hours. Hence, a supplementary air-conditioning system seems inevitable.

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1. Introduction

The growing importance of energy efficiency has resulted in a search for new building heating and cooling concepts. Thermal activation of the concrete core is an example of such a technique enabling the efficient use of energy while maintaining thermal comfort. Already used in the 1930s, the modern equivalent of this technique was first applied in the 1990s. The use in office buildings has increased ever since as described in various monitored case studies [1–6].

The building structure is thermally activated in order to reach thermal comfort inside the building. To this end, water tubes are integrated in concrete slabs, serving as a thermal energy storage for both heating and cooling. The result is a flattening of the peaks in energy demand, which in turn requires lower installed power for heating and cooling [7,8]. TABS are characterized by inconstant room air temperature which floats in between the comfort limits. This is due to the low heat transfer coefficient between the concrete slab and the air in the room as well as the "charging" of the concrete slab while absorbing thermal energy.

Water supply temperatures in the tubes are relatively low for heating (<30 °C), and relatively high for cooling (>15 °C). A combination of TABS and ground coupled heat pumps results in low exergy installations (Fig. 1). As such this holds the promise of an efficient heating and cooling system, achieved through the high performance of the heat pump and direct use of ground storage capacity for cooling [9].

On the other hand, the use of TABS introduces requirements for both the building and HVAC system control. The application of TABS effects the dynamic behaviour of the global system, which requires understanding and control in order to achieve a successful implementation. An initial requirement is a high quality building envelope, because of TABS low available heating and cooling powers. Also, the control of thermal comfort inside the building must be achieved. Heat transfer to or from the TABS is governed by natural convection and radiation and can only be controlled by changing the difference between the TABS surface temperature and the surrounding room temperature. Water supply temperatures influence the former with a time constant of around 10 h, whereas the latter is governed by internal gains such as occupation, electrical devices, and lighting. Solar radiation and the outside temperature also play a role [10].

Section 2 of this paper presents monitoring of the HVAC system in a small scale office building. The system, the measurement results with a control strategy unadapted to TABS and the effect on

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Table 1

Parameters of the measured building equipped with TABS and a heat pump-direct ground cooling system.

Building parameters	
Heated volume (m ³)	3278
Heated area (m ²)	993
Transmission area above the ground (m ²)	1534
U-value external wall/roof/ground slab (W/(m ² K))	0.35/0.36/0.44
U-value total (W/(m ² K))	0.54
Glazing: U-value (W/(m ² K)); g-value (%)	1.7; 40
Percentage of glazing (%)	46 ^a
Installed heating power (kW)	50 ^b
Installed cooling power (kW)	35
Overall electricity use in 2006 (kWh _{el} /m ²)	94 ^c

^a Total glazed area is 706 m², of which 56% is facing South.

^b Only 20 kW of this installed power is used in regime.

^c This equals 234 kWh_{prim}/m² with an electricity conversion factor of 2.5.

The ground slab is a traditional floor heating system, whereas the first floor and the roof slab are TABS. Room comfort is guaranteed by the TABS, together with supplementary heating or cooling by a roof top air handling unit (AHU). Terminal reheat units heat the supply air just before entering the rooms, if necessary. In heating mode, the heat pump heats a buffer tank from where a collector feeds the terminal reheat units, the TABS and the AHU. The TABS and AHU have their own temperature control, while the terminal reheat units use directly the hot water from the buffer tank. While cooling, the heat pump is bypassed and the TABS and AHU are directly connected to the ground water heat exchanger (Fig. 1).

The building is divided into a South and North zone with a separate control. The room temperature is the main controlled parameter of the installation. At the start of the measurements TABS cooling was activated as soon as the room temperature rises above 22.5 °C, and TABS heating started for room temperatures below 21 °C. This narrow dead band control is typically applied in the case of fast reacting systems, such as radiators or forced convection systems. It was applied in this case to the slow reacting TABS.

Each terminal reheat unit has a separate control with a fixed set point of 19 °C but manually adjustable in a 3 °C range. The building management system has no influence on this setting.

The building management system logs several data, such as room air temperatures, water temperatures, air temperatures in the air handling unit and valve positions. Water flow information is not available, so energy calculations are not possible with a reasonable accuracy.

2.2. Measurement results

The analysis of the measurement results focuses on the evaluation of the control strategy applied. Data between May 2006 and March 2007 reveal that the control strategy based on the room temperature is not suitable in combination with TABS. Furthermore, the narrow dead band between heating and cooling deteriorates the performance even more. This control strategy in combination with the high thermal mass results in heating of the TABS during night time and the beginning of the occupation during office hours. Shortly after heating is switched off, cooling starts because internal and external gains increase the room temperature above the cooling set point. Cooling lasts up until a few hours after the occupation is ended. Heating starts again approximately 1 h later. Subsequently, this cycle is repeated. Fig. 2 shows this installation behaviour measured for the open office in the south zone on October 16, 2006.

Although the water in the TABS is heated and cooled in an efficient way, a significant part of the produced heat and cold will

Fig. 2. TABS heating and cooling behaviour, October 16, 2006.

never be used to guarantee thermal comfort in the building. The TABS, which present a large thermal storage capacity in-between the installation and the office room, prevent the thermal energy from entering the room. Heat that has been put into the TABS during night time and early morning is extracted again from the TABS shortly afterwards when cooling starts up. At this short timescale very little of the energy entering the TABS can flow into the room. Since the room air temperature maintains well within a range of 20–23 °C, at this stage, no comfort complaints were reported and it was assumed that the air handling unit and the terminal reheat units did all the work.

2.3. Adjustment of the control parameters

Based on the observed behaviour of the first measurement period, the dead band between the heating and cooling set point was increased mid February 2007 from 1.5 to 3 °C (heating if the room temperature drops below 20 °C, cooling if the room temperature rises above 23 °C). At a larger dead band the operative temperature, defined as the average between room air temperature and concrete surface temperature, risks jumping outside the typical comfort limits of 20–24 °C. However, this measure was the simplest to take without having to change system control strategy thoroughly. The adaptation led to shorter cooling and heating periods as shown by measurements of March 12, 2007 (Fig. 3).

The day of March 12, 2007 is chosen because it has comparable climatic characteristics as the observed October 16, 2006, shown in Fig. 2. October 16th is a Monday with a mean day temperature of 10.6 °C and a clear sky during the whole day. The relative solar radiation time was 89% [16]. The 3 previous days were characterised by a little higher mean day temperature, but a relative solar radiation time of 48%, 34% and 31%. March 12, also a Monday, had a mean day temperature of 8.6 °C and also a whole day of clear sky. The relative solar radiation time was 91%. The 3

Fig. 3. TABS heating and cooling behaviour, March 12, 2007.

$$\text{Tube node : } C_w \frac{dT_w}{dt} = \frac{1}{R_x} (T_{cc} - T_t) - \frac{1}{R_w} (T_t - T_w) \quad (1)$$

$$\text{Concrete core node : } C_{cc} \frac{dT_{cc}}{dt} = -\frac{1}{R_{cc-c1}}(T_{cc} - T_{c1}) - \frac{1}{R_x}(T_{cc} - T_t) + \frac{1}{R_{c2-cc}}(T_{c2} - T_{cc}) \quad (2)$$

$$\text{Upper core node : } C_{c1} \frac{dT_{c1}}{dt} = \frac{1}{R_{cc-c1}}(T_{cc} - T_{c1}) \quad (3)$$

$$\text{Lower concrete node : } C_{c2} \frac{dT_{c2}}{dt} = -\frac{1}{R_{c2-cc}}(T_{c2} - T_{cc}) + \frac{1}{R_{r-s} + R_{s-c2}}(T_{room} - T_{c2}) \quad (4)$$

$$\text{Room node : } C_{room} \frac{dT_{room}}{dt} = -\frac{1}{R_{r-s} + R_{s-c2}}(T_{room} - T_{c2}) + G_{day} + G_{night} \quad (5)$$

Heat losses during night time and heat gains during occupation time are simplified to a heat gain profile (G_{day} and G_{night}) as shown in Table 3. This profile is based on the results of the heating and cooling load calculation for an October day in the south zone of the measured office building, comparable to the one of October 16, 2006. This load profile results in an energy balance over 24 h with 4.1 kWh of excess heat which has to be removed from the room in order to reach a steady state situation.

The simplified room model equations (1)–(5) are implemented in Matlab [24] using the state-space notation and solved with the ODE45 function, based on an explicit Runge-Kutta formula of combined 4th and 5th order, the Dormand-Prince pair, with a time step of 1 h. The simulation was run with the same load profile during consecutive days until a steady state situation was reached, defined by:

$$(T_{room-day(i)} - T_{room-day(i-1)}) < 0.0001 \text{ } ^\circ\text{C} \quad (6)$$

This simulation constraint eliminates the influence of initial values in the simulation results.

4. Simulation results

The energy balance over a 24 h period is reached with a maximum error of 0.2% for every node over the 4 different simulation cases. It should be noted that reaching steady state took up to a period of 19 days, dependent on the control strategy applied. Given the fact that weather conditions change more rapidly, this means that history is important in determining the thermal behaviour of the room.

4.1. Thermal comfort

The operative temperature, defined as the average between room air temperature and concrete surface temperature, is used to evaluate the thermal comfort in the room.

All control strategies, except the one of case 4, are able to keep the operative room temperature within the range as outlined in EN15251 [25] for a class B building, $20 \text{ } ^\circ\text{C} < T_{op} < 24 \text{ } ^\circ\text{C}$, as shown in Fig. 5.

Table 3

Heat gain schedule used for the simulation.

Heat exchange occurring	Heat gain profile
19–8 h: no occupation, heat losses through building envelope	$G_{night} = -8 \text{ W/m}^2$
8–19 h: occupation, heat gains from people, appliances and solar radiation	$G_{day} = 28 \text{ W/m}^2$

Fig. 5. Operative room temperatures for the different control strategies.

Fig. 6. Air, operative and concrete surface temperatures in case 4.

In case 4 precooling during the night causes the operative temperature to drop below $20 \text{ } ^\circ\text{C}$ in the early office hours. However, because the temperature of the concrete ceiling is approximately the same as the room temperature in that first hour, the operative temperature rises quickly above $20 \text{ } ^\circ\text{C}$, due to the heat gains occurring. It is only in the next hours, when a temperature difference is established between room and ceiling, that the TABS can dissipate cooling power to temper the room temperature rise, caused by the heat gains. This behaviour, as shown in Fig. 6, is in agreement with typical TABS temperature profiles [7,8].

4.2. Heating and cooling on-off times

The simulation results indicate substantial differences in heating and cooling system behaviour for the four control strategies examined. Table 4 shows the on-off times for heating and cooling for the different control strategies. Case 2 represents the situation as it was initially measured in the office building.

The simulation confirms the on/off behaviour as monitored and presented in Figs. 2 and 3: the narrow dead band in case 2 results in a maximum of 2 h between switching from heating to cooling or vice versa. Changing the dead band to $3 \text{ } ^\circ\text{C}$ in case 3 improves the situation a little: 2 h between the heating and cooling period and 5 h between cooling and heating. Case 4, with the 4 h of cooling during the night, is a major improvement in eliminating the alternation between heating and cooling, compared to cases 2 and 3.

4.3. Analysis of the control strategy efficiency

A need for thorough analysis was derived from the measurements indicating that the TABS did not participate efficiently in supplying thermal power to the room in order to control room

Table 4

On-off times of heating (H) and cooling (C) for the different control strategies; (0) means no heating and no cooling.

Hour	2		4		6		8		10		12		14		16		18		20		22		24	
Case 1	0	H	H	H	H	H	H	H	H	0	C	C	C	C	C	C	C	C	C	0	0	0	0	
Case 2	H	H	H	H	H	H	H	H	H	0	C	C	C	C	C	C	C	C	C	C	C	0	0	
Case 3	0	0	0	H	H	H	H	H	H	0	0	C	C	C	C	C	C	C	C	C	C	0	0	
Case 4	C	C	C	C	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	

temperatures. The simulation results enable an in-depth analysis of the energy flows from the TABS into the room and from the water circuit into the TABS. To quantify the effect of the control strategies, the ratio between these energy flows over a 24 h period is studied. This ratio give an indication of the control strategy efficiency, as represented by equation (7):

$$\eta_{\text{control strategy}} = \frac{\text{heat exchanged between TABS and room}}{\text{heat exchanged between water and TABS}} \quad (7)$$

The results presenting the energy flows cumulated over one day are shown in Fig. 7. In case 1, the sum of the heat and cold put into the room add up to 4.1 kWh net cooling. This equals exactly the amount of excess heat supplied to the room by means of the

assumed load profile. Fig. 7 shows the low efficiency of the control strategies based on a dead band: in the case of heating 15% (1.1/7.5) for a dead band of 1.5 °C (case 2) and 16% (1.0/6.2) for a larger dead band of 3 °C (case 3). In the case of cooling, the control efficiency is 45% (5.2/11.6) and 50% (5.1/10.3), respectively. The remainder of the energy which was put into the TABS is simply exchanged between the heating and cooling system. For case 2, 6.4 kWh of heat is extracted again by cooling. For case 3 this is 5.2 kWh. Enlarging the dead band (case 3) improves the control efficiency only slightly compared to the initial situation (case 2).

In the office building studied, this means that during the night the heat pump extracts heat from the ground water, converts it

Fig. 7. 24 h cumulative energy flows (kWh) from the load to the room and from the room to the water distribution system (via the ideal emitter for case 1 and via the TABS for cases 2, 3 and 4). (Case 1: set point heating = 21 °C, set point cooling = 22.5 °C; case 2: set point heating = 21 °C, set point cooling = 22.5 °C; case 3: set point heating = 20 °C, set point cooling = 23 °C; case 4: cooling from 0:00 am until 4:00 am)

into heat at a higher temperature level by using electricity and injects it into the building. With the heat gains increasing during office hours, room temperature rises and cooling starts. Heat, supplied during night time, is removed from the building to the ground water via the heat exchanger. For case 2, 85% (6.4/7.5) and for case 3, 84% (5.2/6.2) of night time heat is not used to control room comfort.

The night time operation control of the circulation pump (case 4) yields a high efficiency. The value is even above 100% because during night time the concrete slabs are not only activated from the inside by the cooled water flowing through the tubes, but also by the room air which is at lower temperature than the surface temperature of the slabs. In Fig. 7 this appears as the 0.4 kWh of heat entering the room although there is no heat supplied.

4.4. Analysis of the impact of the control strategy on primary energy use

The conclusions with respect to the control strategy efficiency can also be presented in terms of primary energy use. To calculate the primary energy use corresponding to the different simulation cases examined in this paper, the following system efficiencies are assumed:

- Case 1 heat production: $\eta = 0.85$ (gas fired boiler).
- Case 1 cold production: EER = 3.2 (chiller).
- Case 2, 3, 4 heat production: SPF = 4.25 (water/water heat pump).
- Case 2, 3, 4 cold production: EER = 12 (direct ground cooling).
- Primary energy conversion factor for natural gas: 1.0 [26].
- Primary energy conversion factor for electricity: 2.5 [26].

With these system efficiencies and conversion factors, Table 5 shows the primary energy use for the four simulated cases.

Case 1 results in a primary energy use which is considerably lower than cases 2 and 3, respectively, 38% (1–4.3/6.8) and 26% (1–4.3/5.8) less. Although the system components used in case 2 and case 3 are energy efficient, unadapted control strategies result in higher primary energy consumptions compared to conventional HVAC systems. Despite the fact that case 3 is a far from ideal control, the very simple measure of enlarging the dead band from 1.5 to 3 °C results in a primary energy use reduction of 15%, without having a noticeable effect on thermal comfort.

The control strategy of case 4 results in a very low primary energy use: an 87% (1–0.9/6.8) and 85% (1–0.9/5.8) reduction compared to, respectively, cases 2 and 3. On the other hand, due to the large time constant of the TABS, the thermal response is not adequate enough to guarantee the desired thermal comfort in all circumstances. Therefore, a combination with a fast reaction

system seems appropriate. The simulation results indicate that the night time operation control strategy and its combination with supplementary fast reaction systems should be subject to further optimisation, both in control algorithm and in implementation in real buildings.

5. Conclusions

The control strategy in a building equipped with TABS is vital to obtain energy efficient heating and cooling. Measurement data from a small scale office building indicate that the use of conventional control strategies results in suboptimal operation. In this building, room air temperature feedback control with a small dead band between the heating and cooling set points, determines the HVAC-system operation mode. Due to the large time constant of TABS, switching between heating and cooling occurs in too short a time frame. This results in heat exchanged between both regimes through the thermal energy storage in the TABS. This paper describes a simplified room model, representing the dominant time constants of the building zone and zone loads. The model proves adequate to gain insight into the effect of the control strategy on heating and cooling system behaviour. Model simulations reveal that only 45% of the cold and 15% of the heat produced are actively used to control room temperatures. The remainder is exchanged between the heating and cooling system. Doubling the dead band between the heating and cooling set point from 1.5 to 3 °C, shows that 50% of the cold and 16% of the heat produced is actively used to control room temperatures. In terms of primary energy use, this means a 15% reduction, which is significant, especially compared to the simplicity of the measure taken. The primary energy use difference between the room temperature feedback control and a typical TABS control strategy, such as night time operation of the water circulation pump, is more than 85%. Even more remarkable, a gas fired boiler and chiller system uses 38% less primary energy than the implemented feedback control.

Consequently, unadapted control of the TABS-heat pump-direct ground cooling system has a dramatic impact on the energy performance of the overall system. This can even lead to higher primary energy use than a conventional installation consisting of fast reacting emitting systems, a gas fired boiler and a chiller. On the other hand, night time operation control has problems achieving thermal comfort. Real systems will certainly encounter these problems, because, in contrast to the simulations presented in this paper, the future running time of the circulation pump will be estimated by the measured system behaviour of previous days. A supplementary, fast reaction system, such as conditioned ventilation air, is inevitable in this case.

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Table 5
Energy use in simulation cases 1–4.

Case	Net [kWh]	System [kWh]	Primary [kWh _{prim}]	Primary total [kWh _{prim}]
1 (heating) ^a	0.5	0.6	0.6	4.3
1 (cooling) ^b	4.6	1.5	3.6	
2 (heating) ^c	7.5	1.8	4.4	6.8
2 (cooling) ^d	11.6	1.0	2.4	
3 (heating) ^a	6.2	1.5	3.6	5.8
3 (cooling) ^b	10.3	0.9	2.1	
4 (heating) ^c	0.0	0.0	0.0	0.9
4 (cooling) ^d	4.1	0.3	0.9	

^a Gas fired boiler.

^b Chiller.

^c Heat pump.

^d Direct ground cooling.

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