Monitoring and Data Analysis of two Low Energy Office Buildings with a Thermo-Active Building System (TABS)

D. Kalz, J. Pfafferott and S. Herkel

Fraunhofer Institute for Solar Energy Systems
Heidenhofstr. 2, 79110 Freiburg i.Br., Germany
e-mail: doreen.kalz@ise.fraunhofer.de

ABSTRACT

A promising approach to reduce the primary energy demand of office-buildings without violating thermal comfort is passive cooling by thermo-active building systems (TABS). The presented study introduces two low-energy office buildings within the framework of the German programme ENOB which are conditioned by TABS mainly supplied by geothermal energy. Both buildings aim at a maximum primary energy consumption for heating, cooling, ventilation and lighting of 100 kWh/(m²a). Long-term monitoring data of these buildings are evaluated according to thermal comfort, energy consumption of the building and the auxiliary equipment.

KEYWORDS

Low energy office building, thermo-active building systems, monitoring, passive cooling, energy efficiency

INTRODUCTION

Primary energy demand of new office buildings is dominated by the electricity demand for lighting, ventilation and air conditioning. Figure 1 portrays the primary energy consumption of commercial buildings, comparing: (i) the existing building stock, (ii) typical new constructions as well as (iii) energy optimized buildings, and (iv) two monitored and evaluated buildings within the German supportive program ENBau:Monitor (www.enbau-monitor.de). Office buildings have experienced a continuous decrease in heating demand following the development of stricter building codes. This increased efficiency of the thermal envelope has been accompanied by higher electricity demands.

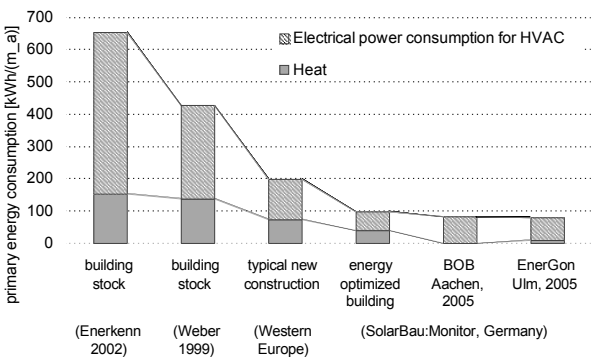

Figure 1 : Comparison of primary energy consumption (heat and electrical power consumption) [kWh_{prim}/(m²a)] for the following buildings (from left to right) : Existing administrative building stock (determined by measurements in 1999 and 2002, [1]), typical new constructions, energy optimized buildings (within the German supportive programme ENBau:Monitor, [2]), as well as measurements from the two introduced low-energy buildings.

A core technology to reduce the primary energy demand of office-buildings without violating thermal comfort utilize the building's thermal inertia to absorb the heat from internal loads during the day and to discharge it at a later time by a natural heat sink (i.e., ambient air, ground water, soil). Extensive research has been surveyed on passive building thermal storage utilization by night ventilation. However, these concepts are limited due to the direct coupling to the ambient air as the heat sink and the required air change rates during heat waves.
Another approach aims at the activation of the building thermal storage by means of thermo-active building systems (TABS) (Figure 2). Basically, TABS are construction elements thermally activated by water or air driven systems that operate with small differences between room air and HVAC system temperatures allowing the use of low temperature heat sources and sinks including heat pumps, borehole heat exchangers, earth-to-air heat exchangers, cooling towers, and solar collectors.
The objective of this study aims at analyzing hydronic thermo-active building systems, in particular concrete core conditioning systems (plastic pipes embedded in the concrete core of the ceiling), for maintaining thermal comfort, as well as reducing primary energy consumption, focusing on the energy consumption of the auxiliary equipment.

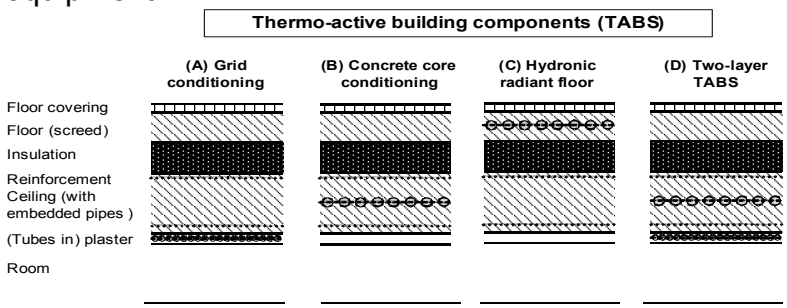

Figure 2 : Construction element sections for common thermo-active building systems (TABS).

BUILDING DESCRIPTION AND MONITORING

To estimate the potential of concrete core conditioning systems referring to thermal comfort and energy efficiency, two low-energy office buildings (Table 1) are monitored and evaluated (described in detail in [1] and [2]). Despite of different approaches for architecture and building energy concepts, both buildings abstain from area-wide air conditioning in favour of passive cooling and strive for: (i) an annual primary energy consumption of maximum 100 kWh/(m²a) for heating, cooling, ventilation and lighting, (ii) reduced solar heat gains by solar control devices, and (iii) low-energy office equipment.
During the operation hours the ventilation strategy uses hybrid ventilation in the offices depending on operation time and user behavior. The supply air gets conditioned by borehole heat exchangers and by earth-to-air heat exchangers. Both ventilation concepts include in winter heat recovery from the exhaust air which is essential to reduce the annual heating demand which is in BOB 25.0 kWh/(m²a) and in EnerGon 21.7 kWh/(m²a).
Employing the soil as a natural heat sink in summer, borehole heat exchangers (BHE) provide chilled water within a temperature range of 16 to 22°C to the concrete core conditioning system which delivers the cold to the office rooms. In winter the buildings use either geothermal heat supplied by borehole heat exchangers and further treated by a heat pump (BOB) or waste heat from chillers (cooling for server rooms and cold storage room of the cafeteria) and district heat (EnerGon). The

concrete core conditioning system serves in the heating and cooling mode in both buildings as the only heat delivery system. Over the course of three years the buildings' energy performance was monitored within a high time resolution considering the demand for heating, cooling and ventilation, operative room temperature, mass flow rates, energy consumption of auxiliary equipment as well as climatic site conditions.

Figure 3: Two low-energy office buildings in Germany. Left: EnerGon, Ulm and right BOB, Aachen [1].

Table 1: Building key information on the design, the energy concept and climate site conditions (2005).

Building key information

	net floor area [m²]	gross volume [m³]	no. of floors	Operation hours	U-value (exterior walls) [W/(m²K)]	area/ volume ratio [m^{-1}]	ambient temperature [°C]		
							annual mean	max. monthly mean	min. monthly mean
EnerGon	6,911	32,223	5	7am-7pm	0.13	0.22	8.0	17.4	-2.8
BOB	2,072	7,675	4	7am-6pm	0.17	0.37	11.5	19.8	2.2

Energy concept

	ventilation	heating	Cooling	borehole heat exchangers	TABS
EnerGon	mechanical ventilation, supply air conditioned by BHE, EAHX, HR (65%)	TABS, WH, DH	TABS, BHE,	40, 120 kW, 100m deep	5,000 m²
BOB	mechanical ventilation, supply air conditioned by BHE, HP, HR (75%)	TABS, BHE, HP	TABS, BHE	28, 55 kW, 45 m deep	2,080 m²

Borehole heat exchanger (BHE), earth-to-air heat exchanger (EAHX), heat recovery (HR), thermo-active building systems (TABS), waste heat (WH), district heat (DH), heat pump (HP).

OPERATIVE ROOM TEMPERATURES

Low energy commercial buildings with passive cooling provide good thermal comfort in summer, if the building is designed for low solar and internal heat gains with an adequate heat storage capacity and a sufficient heat sink. The discussed comfort criteria consider the room temperature (RT in [°C]) as a function of the ambient air temperature (AT in [°C]). In the following the buildings are evaluated referring to their thermal comfort according to two comfort criteria which use different time periods of the ambient air temperature ([2], [4] and [5]):

- prEN 15251 takes the monthly ambient air temperature AT_m into account. The comfort temperature is 22 °C in winter an RT_c=17.8°C+0.31*AT_m in summer.
- The Dutch ISSO 74 considers the thermal adaptation. The comfortable room temperature responds to the running mean ambient air temperature of the last three days AT_{rm} using the same formula as prEN 15251 but with another reference temperature: RT_c= 17.8°C+0.31*AT_{rm}.

The results from a one year monitoring (2005) on an hourly base have been analyzed regarding the operative room temperature during the time of occupancy (8 am to 6 pm) according to the two stated comfort criteria: Figure 3 shows room

temperatures for chosen offices and the mean value of comfort votes for the whole building. The mean comfort value demonstrates, that the thermal comfort criteria is infrequently violated, taken 90% satisfied persons into account. Especially during the summer period the temperatures stay within the required comfort range and do not exceed 27°C. Besides, occupant comfort is improved since radiant heating/cooling is generally considered more comfortable than forced-air methods as it provides draft-free and noise-free cooling with improved operative temperatures. The ground is an independent heat sink, which thermally decouples the building from the ambient air. Hence, this cooling concept provides cooling energy to the building even at high ambient air temperatures. Therefore, it can modulate heat waves, smooth out room temperature steps and, hence, can significantly enhance the thermal comfort.

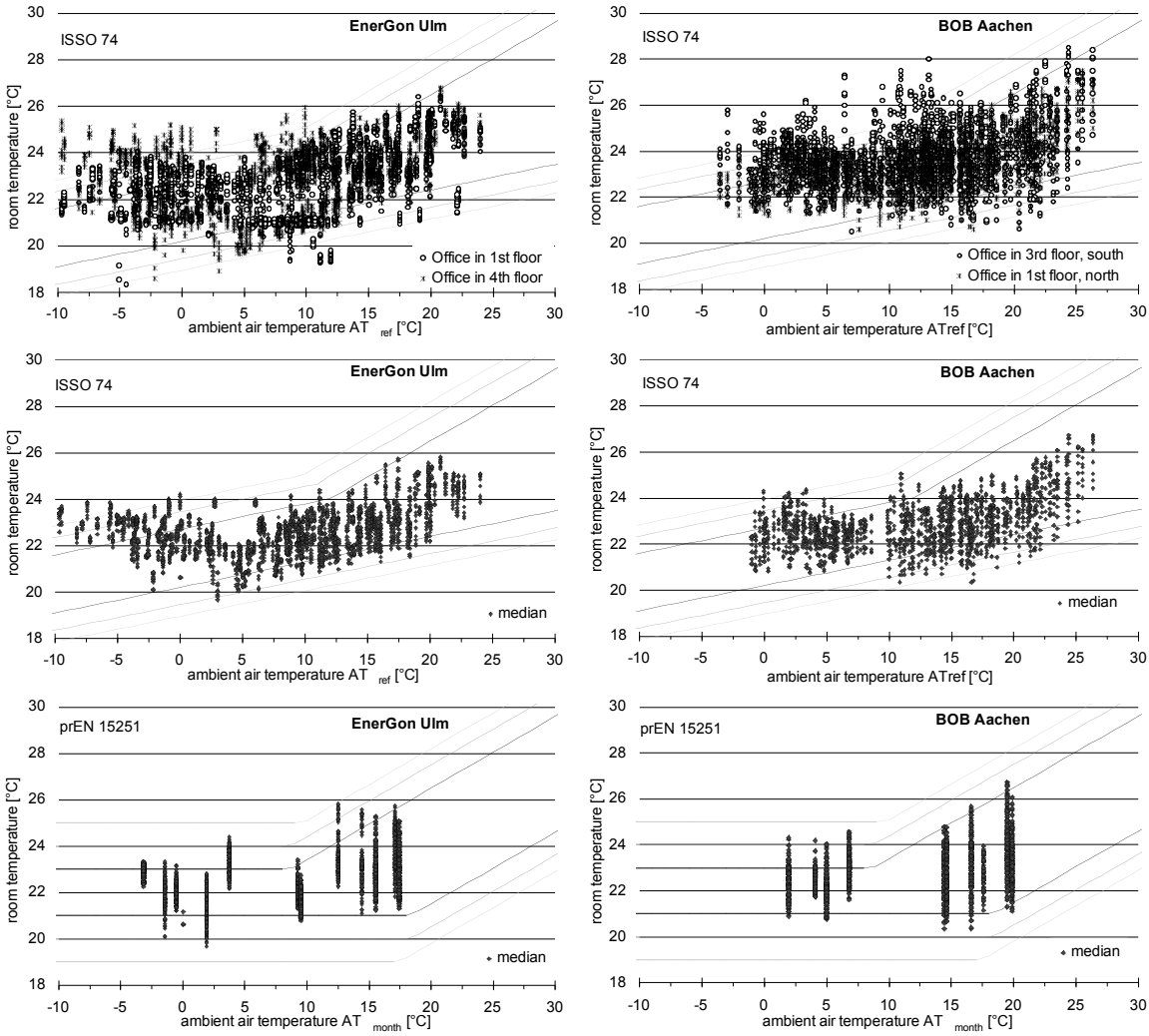

Figure 4: Thermal comfort for the buildings EnerGon in Ulm (left) and BOB in Aachen (right) in 2005: Room temperature for chosen offices and average temperature of all offices. The prEN15251 and the NPR-CR 1752 charts show the temperature range for 90 (black line), 80 (dark grey line) and 65% (light grey line) users satisfied with the room temperature.

ENERGY PERFORMANCE AND EFFICIENCY

This section describes the annual energy performance of both buildings expressed by heated net floor area-specific energy intensities in units of [kWh/(m²a)] with

respect to the following two classes of energy as defined by the umbrella document of the EPBD ([3]):

- Primary energy: Energy that has not been subjected to any conversion or transformation process. Though different for each country the primary energy conversion factors selected for this study are 3.0 for electricity, 0.2 for biomass and 0.7 for cogeneration using fossil fuels.
- End energy use: Energy input to the heating, cooling or hot water system to satisfy the energy need for heating, cooling or hot water, respectively.

Both buildings accomplish the stated aim of a maximum primary energy consumption of 100 kWh/(m²a) and a maximum end energy use of 60 kWh/(m²a) (Table 2, Figure 5). The special feature of the BOB building is the fact that electricity is the primary energy source which supplies the entire heating and cooling demand through a heat pump and borehole heat exchangers. Considering a primary energy conversion factor of 3.0 for electricity explains a primary energy consumption which is equal to the EnerGon, although the end energy use is just half the amount of EnerGon. The electrical power consumption of the borehole heat exchangers (BHE) is lower at the EnerGon, since in winter the BHEs condition the supply air only but do not contribute to the heat demand of the TABS. The pump system of the EnerGon building for distributing heat/cold to the TABS consist of one main pump resulting in a reduced electrical power consumption, whereas in the BOB building the hydraulic system supplying the TABS contribute to 10.2% of the annual primary energy consumption.

Table 2: Building key information on energy performance [kWh/(m²a)].

	heat consumption [kWh/(m²a)]	end energy use[1] [kWh/(m²a)]			primary energy consumption[1] [kWh/(m²a)]			electrical power consumption [kWh/(m²a)] and percentage of annual primary energy consumption			
		heat	electricity	total	heat	electricity	total	BHE	TABS	ventilation	lighting
EnerGon 2005	21.7	23.4	23.4	46.8	11.7	70.3	82.0	2.5 (9.2%)	1.5 (5.5%)	8.6 (31.5%)	7.2 (26.3%)
BOB 2005	25.0	/²	27.4	27.4	/³	82.2	82.2	5.2 (19%)	2.8 (10.2%)	4.2 (15.3%)	10.4 (38%)

[1] Energy consumption for HVAC appliances (heating, cooling, ventilation and lighting). The value does not include the energy consumption for office equipment and cafeteria. ² Geothermal energy and heat pump. ³ Primary energy source is electricity.

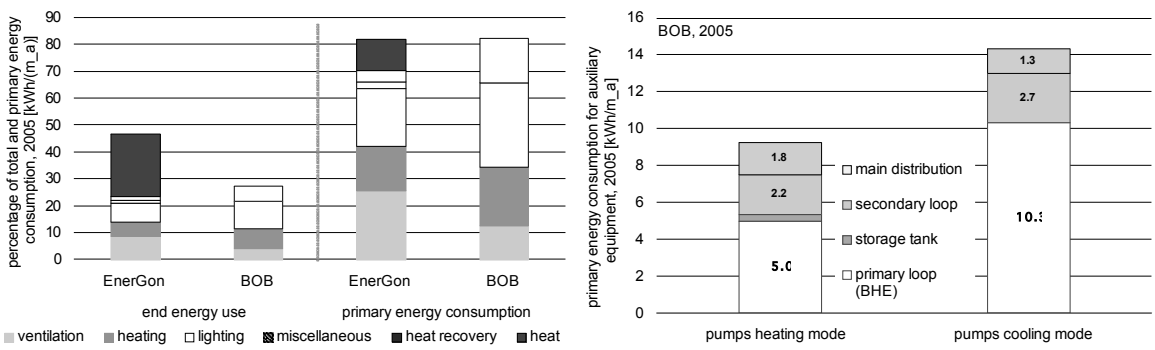

Figure 5 : Detailed analysis of the annual end energy use and primary energy consumption for heating, cooling, ventilation and lighting for both office buildings. Left: Energy consumption [kWh/(m²a)] for the specific HVAC categories: electricity for ventilation, heating, lighting, miscellaneous (cooling, hot water, etc.) and heat recovery, as well as heat (district heat). Right: Breakdown of the primary energy consumption for auxiliary equipment (pumps for the primary and secondary loop, as well as the main distribution pump for the TABS) in heating and cooling mode exemplarily for the BOB building. The annual primary energy consumption for auxiliary equipment amounts to 23.6 kWh_{prim}/(m²a) (heating mode: 9.3 kWh_{prim}/(m²a) and cooling mode: 14.3 kWh_{prim}/(m²a)) or 29% out of the total annual primary energy consumption (2005).

The efficiency of building systems can be described by a coefficient-of-performance (COP) that is the ratio of the total energy provided by the system to the amount of electricity required to operate the system. Considering exemplarily the BOB building, the following COPs for the heating mode can be determined according to a defined boundary: The efficiency of the heat generation results in 4.3 kWh_{therm}/kWh_{el} taking into account the electrical energy consumption of the compressor and the pump in the primary loop. If the boundary for determining the COP comprises the energy consumption for the hydraulic system as well than the COP results in a reduced value of 3.4 kWh_{therm}/kWh_{el}.

CONCLUSION AND FUTURE WORK

Passively cooled low-energy office buildings provide a high thermal comfort even without mechanical cooling, when the heat dissipation in summer is enhanced by a thermo-activated building system (TABS). These surveyed buildings demonstrate that well-designed TABS in low-energy buildings as the only heat delivery system can guarantee thermal comfort in winter, provided that heat losses are minimized though heat recovery and small U-values for the construction. In summer the thermal comfort according to adaptive comfort criteria are infrequently violated, taken 90% satisfied persons into account.
Low-energy office buildings which employ natural low-temperature heat sinks and sources can reduce their primary energy consumption by 50% compared to typical new commercial building constructions (Figure 1). A critical analysis of the hydraulic system components towards energy consumption for auxiliary equipment (pumps) further reveals an optimization potential to reduce electrical power consumption. In the BOB building 29% of the primary energy consumption is consumed by the hydraulic system for distributing heat/cold through the building. The investigation of different control strategies for pumps and TABS, respectively, as well as a load management by means of a model-based analysis of measurements will foster to significantly reduce the energy consumption for auxiliary equipment and therefore to enhance the entire system's efficiency.

Acknowledgements

This study was funded by the German Ministry of Economics and Labour BMWi under the programme "Energy Optimized Building" (BMWi 0335007C). Monitoring, data acquisition and data evaluation is a time consuming task. The authors would sincerely like to thank I. Repke (FH Köln), G. Lindemann (FH Ulm) and P.Obert (FH Ulm).

References

[1] Voss, K., Löhnert, G., Herkel, S., Wagner, A. and Wambsganß, M. (2006): Bürogebäude mit Zukunft – Konzepte, Analysen, Erfahrungen, Solarpraxis Berlin, 2nd edition, ISBN-10: 3-934595-59-6.

[2] Voss, K., Herkel, S., Löhnert, G., Pfafferott, J. and Wagner, A. (2006): Energy efficient office buildings with passive cooling – Results from a Research and Demonstration Programme. Proceedings of 4th European Conference on Energy Performance and Indoor Climate in Buildings, Lyon, France.

[3] CEN/BT WG 173 EPBD (2006): Explanation of the general relationship between various CEN standards and the Energy Performance of Buildungs Directive (EPBD).

[4] Gossauer, E., Leonhart, R. and Wagner, A. (2006): Workplace occupant satisfaction at workplaces – a study in sixteen German office buildings. Proceedings of Windsor Conference on Comfort and Energy Use in Buildings, Windsor, UK.

[5] Pfafferott, J., Herkel, S., Kalz, D. and Zeuschner, A. (2006): Comparison of low-energy office buildings in summer using different thermal comfort criteria. Proceedings of Windsor Conference on Comfort and Energy Use in Buildings, Windsor, UK.