Evaluation of the energy efficiency of thermo-active building systems with integrated phase change materials in residential buildings employing a rainwater cistern as environmental energy and optimization of the operation by means of suitable control strategies

Summary

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Objective and Methodology of Research Project

This work evaluates a novel heating and cooling concept employing thermo-active building systems and environmental energy harnessed from 22-m³ rainwater cisterns for a 290-m² low energy residential building in Germany. The building strives for a significantly reduced primary energy use based on carefully coordinated measures such as a high quality building envelope provided by vacuum insulated panels, a supply and exhaust air system with heat recovery, reduced solar heat gains, and the integration of thermal solar collectors and photovoltaic into the plant system.

On this premise, a comprehensive long-term monitoring in high time resolution was carried out over the course of two years (2006-2007). The monitoring was accompanied by a commissioning of the building performance. Measurements comprise the energy use for heating, cooling, and ventilation, as well as the auxiliary equipment, the performance of the environmental heat source/sink, thermal comfort, air quality, and local climatic site conditions.

The analysis focuses on the performance and the efficiency of the rainwater cistern as a natural heat sink. First, the work discusses the performance of the thermo-active building systems, investigates the occupant thermal comfort, and determines the efficiency of the cooling system. Secondly, various operation and control strategies for the cooling plant are investigated by means of a validated building and plant model in the dynamic simulation environment TRNSYS. The optimization is carried out in terms of energy efficiency, occupant thermal comfort and the availability of the rainwater cisterns over the summer months.

Keywords: residential building, long-term monitoring, thermal comfort, environmental heat source/sink, thermo-active building systems, energy efficiency, rainwater cisterns

Introduction of the investigated Building and Technical Plant

Building: The building with a net floor area of 290 m² (three floors, north-south alignment) strives for a significantly reduced primary energy use based on carefully coordinated measures: a high quality building envelope by means of vacuum insulated panels, an air-tight building envelope in conjunction with basic and hygienically necessary air ventilation, heat recovery, and reduced solar heat gains (solar shading).

Ventilation system: A supply/exhaust ventilation system with heat recovery in winter (efficiency 80%) provides 200 m³/h fresh air to the building. Additionally, an earth-to-air heat exchanger (length 10 m) is installed to precool and preheat, respectively, the outdoor air, therefore reducing the cooling/heating demand.

Natural heat source/sink: Rainwater is collected in two underground cisterns and serves as heat source/sink. The cisterns are made of concrete and have a total volume of 23 m³. The excavation depth required for installing the cisterns is only 2 to 3 m. A rainwater storage can be a suitable energy source for heating and cooling since its temperature is more stable than the ambient air temperature. However, the usability of this environmental energy greatly depends on the type of ground, the frequency of precipitation, the amount of collected rainwater, the operation of the system (continuous cooling or just peak load cooling), and the heating/cooling demand of the building.

Heating system: Primarily, a 12-m² thermal collector plant provides heat for domestic hot water and space heating by feeding a stratified hot water storage tank with a volume of 1,000 liters. Further, the two cisterns serve in an open-loop system as natural heat source for a heat pump with a thermal power of 6.7 kW. Water is extracted by a submerged pump from the warm cistern, used by the heat pump and injected again in the cold cistern. The heat pump supplies the stratified hot water storage tank as well. An electrical heater integrated in the stratified hot water storage tank serves a back-up system.

Cooling system: During the cooling mode, only one rainwater cistern (cold cistern, volume 12 m³) featuring an integrated heat exchanger is utilized as heat sinks for cooling the building. A thermo-active building system (TABS) actively incorporates the ceiling and walls (284 m²) and their thermal storage into the energy management of the building. It serves in both the heating and cooling mode as the sole delivery system.

Phase Change Materials (PCM): PCM (microencapsulated paraffin) is integrated in the gypsum board and plaster in order to enhance the thermal storage capacity of the lightweight building construction. The temperature range of the phase change (solid-liquid) is defined as 23 to 26°C with an augmented latent heat capacity of 306 kJ/m² (gypsum board) and 217 kJ/m² (plaster). The PCM storage is charged according to internal and solar heat gains and, therefore, extenuates the development of the operative room temperature. Heat stored in the PCM is actively discharged by the thermo-active building system in combination with the environmental heat sink.

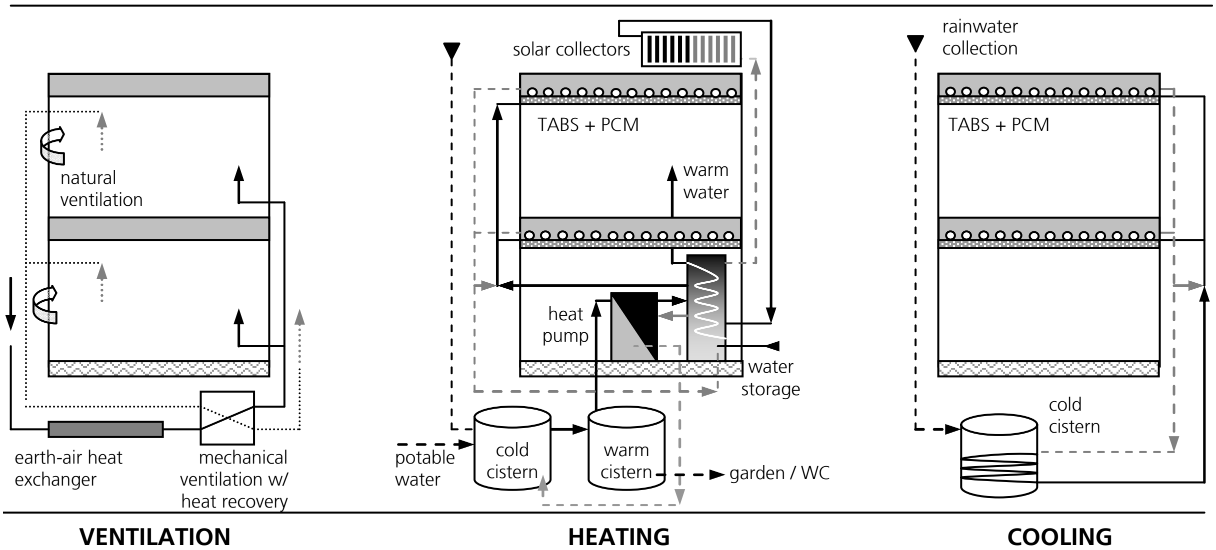

Figure 1: Energy concept: (i) hybrid ventilation, (ii) heating: collected rainwater in cisterns (24 m³) in combination with heat pump and 12 m² solar collectors, (iii) cooling: collected rainwater in cistern (12 m³). Heat/cold delivery to the rooms by thermo-active building system (TABS, 284 m²). Microencapsulated phase change material (PCM, paraffin) in walls and ceilings enhances building's thermal storage capacity.

Summary of Results

Rainwater as Environmental Heat Sink

Temperature development of the rainwater cisterns: During the cooling period, water supply temperatures of the cold cistern range from 10 to 22°C with a distinct thermal layering. Attention has to be paid to the operation of the entire system, since permanent cooling results in fast depletion of the energy reservoir (temperatures above 20°C in summer). The volume of the cistern has to be dimensioned adequately in accordance with the required heating and cooling load of the building. An intermittent operation mode is beneficial for the thermal recovery of the cisterns.

Energy balance of the rainwater cisterns: The energy balance of the rainwater cisterns is driven by four parameters: (i) heat storage (cooling mode) and extraction (heating mode) and the heat gain/loss to (ii) the ground and the surrounding, (iii) the precipitation, and (iv) the backfeed of potable water

(Figure 2: heating). Once the water level in the cisterns falls below a defined level, fresh potable water (temperature 7 to 16°C) is supplied – a total of 95.6 m³ during the period of May to December 2007. Typical of near-surface geothermal systems, the crucial parameter dominating the energy balance of the cisterns is the amount of heat gain and loss to the ground. Surprisingly, both the rainwater and the potable fresh water intake have only a minor effect on the energy balance and, therefore, the temperature development of the cisterns. The major heat loss of the cistern during summer occurs to the surrounding ground (950 kWh/a, which amounts to 8.1 Watt per square meter surface area of the cistern.) In comparison, rainwater only marginally influences the energy balance (47 kWh/a). The heat loss resulting from the intake of fresh water (withdrawal of water for garden and toilets) amounts to 92 kWh/a and is particularly significant in the months of July and August. The extracted cooling energy from the cistern remains in the same order of magnitude during the summer months (June to August).

Energy and efficiency performance: The cooling power of the 12-m³ cold cistern ranges between 0.5 and 2 kW, obviously correlating to the water temperature. During the cooling period from late April until early September, the harvested energy ranges between 200 and 550 kWh/month (2006) and is fairly constant around 300 kWh/month during 2007. The efficiency, expressed as seasonal performance factor, ranges from 3 to 6.8 kWh_{therm}/kWh_{end} and evidently reaches its peak at the beginning of a cooling season. The operation and control of the cisterns are crucial, in order to guarantee the availability of the cisterns during the entire operation period.

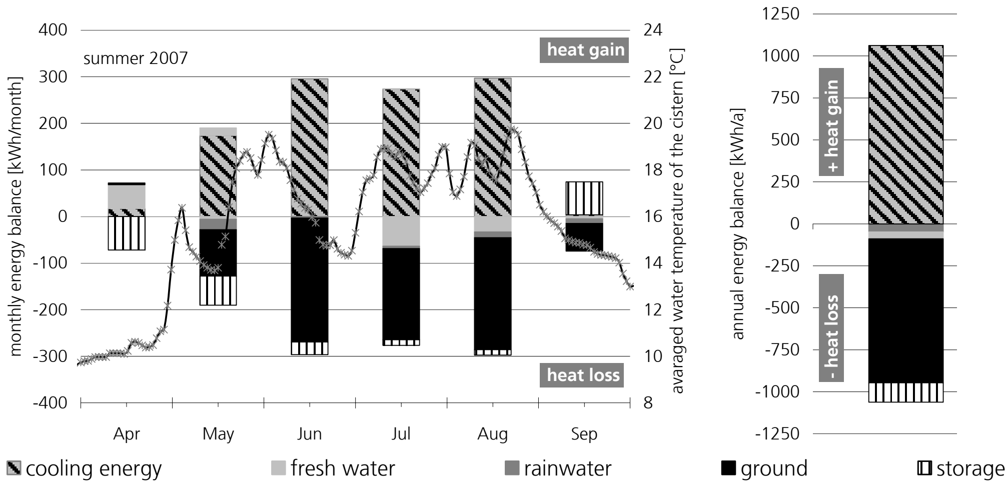

Figure 2: Monthly (left) [kWh/month] and annual (right) [kWh/a] energy balance of the cold cistern over the course of operation from May to September 2007. The energy balance is a consequence of heat storage and the heat loss to the ground, by precipitation and by the backfeed of potable water. Note: Energy storage due to

increase of the water temperature in the cistern. Heat loss to the ground amounts to approximately 8 Watt per surface area (29 m²) of the cold cistern.

Thermo-Active Building System (TABS)

Energy distribution and delivery by thermo-active building system: The water supply temperature to the TABS ranges between 17 and 23° with resulting return water temperatures from 19 to 26°C. Operating mostly in a continuous mode, the temperature differences vary between 0.5 and 2 Kelvin with a delivered cooling energy of 1 to 1.5 kWh/m²month. The temperature difference between ceiling temperature and operative room temperature ranges between one and maximum 4 Kelvin. The analysis of the auxiliary energy use reveals a great potential for savings. The submerged and the circulation pumps are oversized as far as the pressure drops are concerned. Further, the three installed circulation pumps (one for each floor) can be replaced by one pump, thereby reducing the auxiliary energy use. Moreover, the control unit for the TABS has re-implemented standard features usually used in conventional cooling systems (e.g., nighttime set-up) which cause longer operation hours and are, therefore, disadvantageous for the efficiency performance.

End and primary energy use of the building: The primary energy use for heating, cooling and ventilation (without lighting) amounts to 52 kWh_{prim}/m²a. Thus, the auxiliary energy adds 28% to the total primary energy use (15 kWh_{prim}/m²a). This reveals potential for optimization and savings.

Operation and control: The near-surface thermo-active building system requires an operation during the day. In order to reach optimal thermal comfort of the occupants, energy efficiency and availability of the rainwater cistern, it is most beneficial to control the temperature of the water supply so that it remains in line with the ambient air temperature. Controlling the system according to the adaptive comfort model of the EN 15251:2007-08 (operative room temperatures in accordance with the running means of the ambient air temperature) benefits the availability of a moderate water temperature in the cistern. The rainwater cistern as heat sink is then available for cooling over the entire summer period.

Occupant thermal comfort in summer: The dwelling is evaluated in terms of its thermal comfort in summer according to two comfort criteria which are based different time periods of the ambient air temperature: EN 15251:2007-08 and EN ISO 7730:2005. Hourly measurements at the building comprise the dry bulb temperature, the operative room temperature and local climatic site conditions. Since the actual daily presence of the residents in the building is not recorded, it is assumed that thermal comfort has to be provided during 24 hours. Measurements of the operative room temperatures over the course of two years reveal an entirely satisfactory thermal comfort during the summer period. Even at ambient air temperatures above 36°C, the operative room temperatures do not exceed 28°C. The continuous cooling by means of the rainwater cisterns provides sufficient cooling energy to condition the rooms. Considering just the living area on the third floor, the number of hours exceeding the defined comfort class A amounts to 90 (EN15251:2007-08) and to 100 (EN ISO 7730:2005), respectively. Therefore, according to both guidelines the building can be assigned to the comfort class A (resembling 90% satisfied occupants) requiring a cooling energy of 3.7 kW/m²a that is generated with an efficiency of 6.9 kWh_{therm}/kWh_{end}.

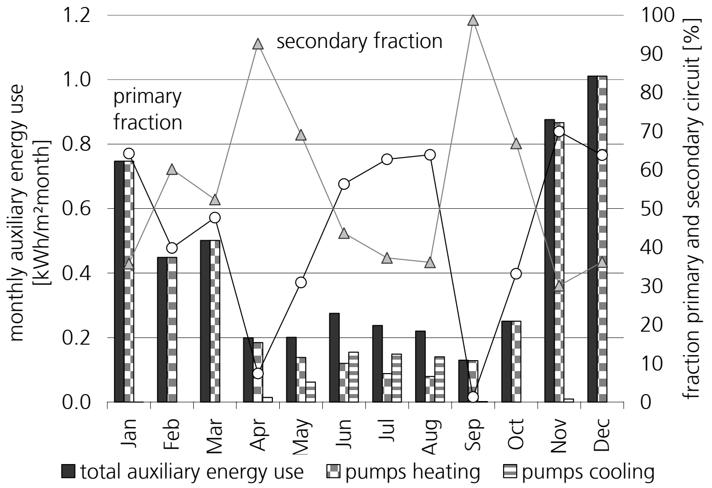

Figure 3: Monthly electrical auxiliary energy use [kWh/m²month] for the generation (primary circuit) and distribution/delivery (secondary circuit) of heating and cooling energy. The fraction [%] of the primary and secondary circuit of the total auxiliary energy use is given on the second y-axis.

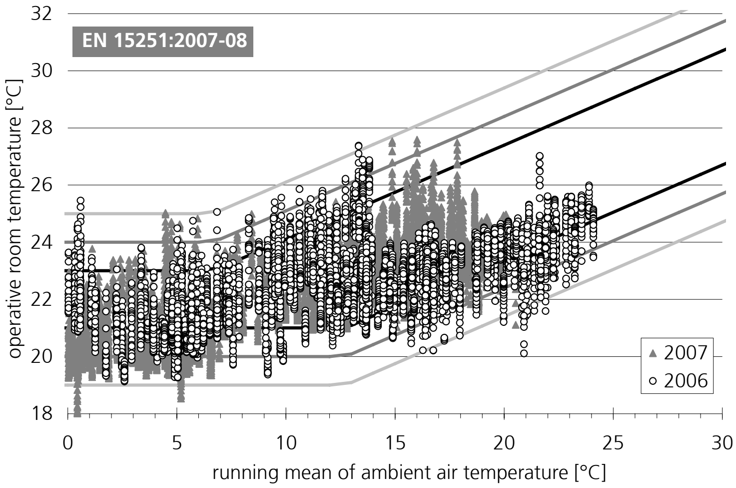

Figure 4: Evaluation of hourly operative room temperatures [°C] in the living area of the third floor over 24 hours according to the comfort guideline EN 15251:2007-08. Charts demonstrate the comfort boundaries for the classes A, B and C resembling a satisfaction of the user around 90, 80 and 65% (black, dark grey and bright grey lines).

Summary and Conclusion

The central findings of the analysis of the energy and efficiency performance of the HVAC system are:

Environmental energy: The energy balance of the cisterns is mainly influenced by the heat loss and gain to the surrounding ground. In the cooling mode, a volume of 12 m² is available which is sufficient (cooling power 0.5 – 2 kW) but requires a load management since continuous cooling results in fast depletion of the energy reservoir (temperatures of cistern above 18°C in summer). The efficiency of the system, expressed as seasonal performance factor, results in 6.9 kWh_{therm}/kWh_{end}.

Energy distribution and delivery by thermo-active building system: The analysis of the auxiliary energy use reveals great potential for savings. The circulation pumps are oversized as far as the pressure drops are concerned. Further, the three installed circulation pumps (one for each floor) can be replaced by one pump, reducing the auxiliary energy use. Moreover, the control unit for the TABS has re-implemented standard features usually used in conventional cooling systems (e.g., nighttime set-up) which cause longer operation hours and are, therefore, disadvantageous for the efficiency performance.

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