Performance of the Building with Three Different Radiant Systems

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Performance of the Building with Three Different Radiant Systems

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Abstract. This study evaluates the potential of thermal comfort enhancement in a modern office building with high ratio of glazed façade and a heating / cooling system with high thermal inertia. Application of proper control strategies for HVAC systems is important to prevent overheating, overcooling and excessive energy consumption. In this paper, the effect of various control settings and strategies on the thermal comfort is studied. The study is performed on a validated simulation model for a representative thermal zone located in a real administrative building, called the Energetikum.

1. Introduction

Modern buildings with the high portion of glazed facade elements are prone to problems with thermal comfort, as big glazed areas are often related to higher energy losses during heating season and overheating of indoor spaces due to direct sunlight over the summer and transition periods [1]. The energy balance is more dynamic, and the energy demand may vary more for highly glazed buildings than for buildings with traditional facades since the glazed alternatives are particularly sensitive to the outdoor conditions. Whereas potential problems with overheating of the interiors during summer can be anticipated, cold days with high solar irradiation when the solar heat gains exceed the energy demand for heating present an important factor in the heating, ventilation and air conditioning (HVAC) design.

Number of radiant system installations has been increasing recently due to their numerous advantages. In low energy buildings, a radiant hydronic system can be installed that can be used both as low temperature heating in winter and as high temperature cooling in summer. Besides of creating a homogeneous thermal environment [2,3] and a uniform air distribution, close to complete mixing [4,5] the advantage of such a low exergy system is that it is suitable for combination with renewable energy sources such as heat pumps and solar collectors. The potential problem of combining lightweight envelope with radiant heating and cooling is represented by the fact that the outside weather conditions, solar irradiance, changes in internal heat gains and small heat accumulation capability of the light-weight facade can result in relatively dynamic changes in thermal balance of the building. If the building is not properly designed and controlled, the radiant system may not be able to respond to these changes fast enough to assure a comfortable thermal environment due to its high time constant. It is therefore an essential task to learn, how to design and control this type of buildings.

2. Description of the experimental object

The experimental measurements for the model validation, computer simulations and optimizations were carried out for a new-type office building called the Energetikum. There are several aspects which make the building modern and new comparing to traditional buildings:

a) The building is a "living laboratory ", where people have offices, and where they perform their everyday working activities. On the other hand, it contains a number of technologies, and it is equipped by hundreds of sensors monitoring the indoor environment, energy consumption and boundary conditions.

b) The building includes three different types of radiant systems that can be run individually or simultaneously, mechanical ventilation, external blinds, and three different types of heat withdrawal systems which can be combined with innovative types of heat pumps.

This building thus allows designing experiments to investigate the effects of real user behavior on the energy consumption, the effects of HVAC design on thermal comfort, and research of alternative energy supply systems, storage technologies and control engineering strategies in 1:1 scale.

2.1. Building envelope

The two-storey building, located in Pinkafeld (Austria) has two types of façade to eliminate the risk of high heating demand during winter, and to provide enough daylight. The glazed light-weight (post and beam) façade is implemented in the parts of the building envelope oriented to the West-South-West (W-S-W), East-North-East (E-N-E) and South-South-East (S-S-E); thereby the solar gains can lower the energy demand for space heating during the heating period. The external blinds prevent the interior from overheating during periods with high solar irradiance. The North-North-West (N-N-W) facade consists of reinforced-concrete walls with 160 mm of thermal insulation. All the transparent parts of the façade are with triple glazing. The heat transfer coefficient of the individual components varies between 0.79 and 1.10 W/ (m^2. K) depending on the ratio of glazed area to total surface area of the component.

2.2. Heating, ventilation and air conditioning (HVAC)

A brine/water heat pump supplies the object with heat and cool. The heat pump exploits the primary energy from energy baskets and helix probes located around the building and from a ground collector under the building foundations. As the area available to exploit the geothermal energy via heat pump is too low to cover the peak heat supply, a gas boiler is installed as the peak source for the heating.

Three independent heat emission systems are installed in the building (figure 1):

- Floor heating/cooling with pipes embedded in concrete, insulated from the concrete core;
- Thermally active core with pipes embedded in the middle of the concrete ceiling;
- Thermally active core with pipes embedded near the surface of the concrete ceiling.

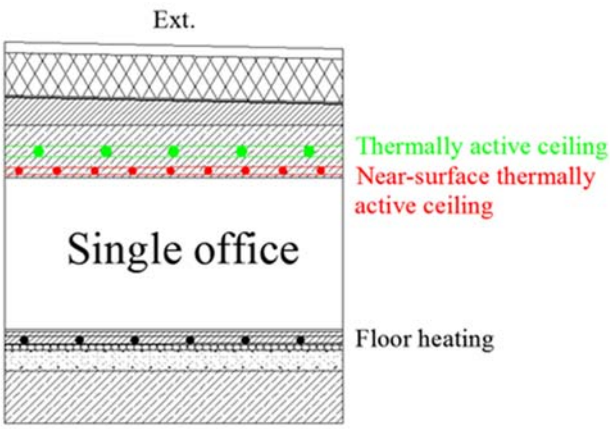

Figure 1. Position of three radiant systems regarding to Single office

The three systems can be operated individually or simultaneously depending on the current demand, each having a separate control loop to allow independent operation. The central air conditioning unit providing adiabatic cooling is installed in the engine room. Each office is equipped by variable air volume mechanical ventilation serving also as air conditioning. The air is supplied to and exhausted from the rooms through rectangular grills.

2.3. Indoor environment assessment and problems definition

Permanent sensors to monitor and control HVAC operation were installed during construction of the building. To supplement and verify the data obtained from the pre-installed permanent sensors, and to help detect the potential problems with the indoor environment and HVAC operation, portable "monitoring-trees" with highly sensible sensors were installed. The monitored indoor environment indicators measured by the portable monitoring devices were: air temperature, relative humidity and carbon dioxide concentration. Single office 1 (SO 1) has been selected as the reference room with regard to its thermal stability.

The results indicate that the desired thermal environment was achieved for only a limited amount of time, in particular due to overheating in winter (21-25 March 2016) and overcooling in summer (23-27 May 2016). Generally, the temperature is above the recommended limit during heating period and below the limit during cooling period [6]. This indicates a significant potential for energy savings and thermal comfort enhancement by adjusting the temperature set points and improving the control strategy, e.g. by optimizing the operation of the PI controllers, shading devices, and the inlet air temperature.

3. Parametric study of the control strategies and settings

Computer simulations of the reference room SO 1 were done to examine the possibilities to minimize thermal discomfort and reduce the energy consumption in heating period. This study aims to investigate the possible improvements by optimizing the shading and HVAC operation. Specifically, the control of ventilation, shading operation, and the type of radiant system were varied to determine the optimum control strategy. Ten reference days were selected in January as well as in March to cover both the very cold and the transient weather period. Sixteen variants (table 1) of control settings and strategies were examined and compared to the initial setting. The simulation model was developed within TRNSYS environment due to its feasibility for transient simulations of HVAC systems.

3.1. Initial settings – variation V1

3.1.1. Variable air volume (VAV) ventilation control. The VAV system maintained the air supply at a constant temperature while individual zone thermostats varied the flow of air to each space to maintain the desired indoor air quality and zone temperature. The maximum of four air change rates was provided by the ventilation system to the single office. The inlet air temperature was stable – 22°C. The air change rate was controlled by a three stage controller depending on the CO_2 concentration of the indoor air. The actual indoor CO_2 concentration was calculated by the mass balance equation:

$$C_i(t) = (C_0 - C_a) \,.\, e^{(-\lambda . t_i)} + C_a + \frac{E \,.10^3}{\lambda \,. V_R} \,.\left(1 - e^{(-\lambda . t_i)}\right) \tag{2}$$

where C_i is the tracer gas concentration indoors (ppm); C_0 is the tracer gas concentration at the beginning of the measurement (ppm); C_a is the tracer gas concentration outside (ppm); λ is the air change rate (h^{-1}); E is the amount of tracer gas emitted per unit time (l/h); V_R is the room volume (m^3); t_i is the time elapsed (h).

3.1.2. Shading system. The shading system represented by external blinds with the solar heat gain coefficient (SHGC) of 0.2 protects the room from redundant solar gains. The shading control depends on the amount of solar radiation.

The blinds position was adjusted depending on the amount of incident solar radiation on the external wall by three stage controller. Reaching the solar radiation value of 800 kJ/h.m^2 caused that the blinds fully cover the window, which results in 80 % reflection of the solar radiation. Otherwise, the shading covered 30 % or 70 % of the window area depending on the actual value of solar radiation.

Table 1. Variants of HVAC setting used in the parametric study

	Heating control			Ventilation control		Shading control	Aim of study
	Floor heating	Ceiling heating	Thermally active ceiling	Air flow rate	Inlet temperature		
V1	PI	0	0	CO2	Stable	Radiation	Ventilation temperature
V2	PI	0	0	CO2	Indoor air temperature + night setback	Radiation	
V3	PI	0	0	CO2 + indoor air temperature	Stable	Radiation	Ventilation flowrate
V4	PI	0	0	CO2 + solar radiation	Stable	Radiation	
V5	PI	0	0	CO2 + night setback	Indoor air temperature	Radiation	Effect of night setback
V6	PI	0	0	CO2 + night setback	Stable	Radiation	
V7	PI	0	0	CO2 + solar radiation	Indoor air temperature + night setback	Radiation	Combined control
V8	PI	0	0	CO2 + indoor air temperature + night setback	Stable	Radiation	
V9	PI	0	0	CO2 + solar radiation + night setback	Indoor air temp	Radiation	
V10	PI	0	0	CO2 + indoor air temperature + night setback	Stable	Indoor air temperatur e	Shading control
V11	PI	0	0	CO2 + indoor air temperature + night setback	Stable	Indoor air temperatur e + radiation	
V12	0	PI	0	CO2 + indoor air temperature + night setback	Stable	Radiation	Radiant systems comparison
V13	0	0	PI	CO2 + indoor air temperature + night setback	Stable	Radiation	
V14	0	0	Day-night	CO2 + indoor air temperature + night setback	Stable	Radiation	Thermal core activation control
V15	0	0	On-off	CO2 + indoor air temperature + night setback	Stable	Radiation	
V16	0	0	Difference between supply and return	CO2 + indoor air temperature + night setback	Stable	Radiation	
V17	PI	0	Day-night	CO2 + indoor air temperature + night setback	Stable	Radiation	

3.1.3. Radiant heating control. Radiant floor heating with a stable flow rate of 190 l/h was implemented in the model to cover the heat demand of the zone. The desired zone inlet temperature was maintained by a three-way mixing valve. The temperature at the source level was controlled according to the running mean ambient temperature (EN 15251). A PI controlling algorithm was applied to minimize the temperature fluctuations and to keep the air temperature at about 21 °C during the occupied time periods and at 18 °C during the night by adjusting the inlet temperature of the floor heating. The PI controller is currently the most appropriate controller in the area of energy efficient radiant heating systems. The PI control algorithm is based on the following equation with two constituents:

$$u(t) = K_p e(t) + K_i \int_0^t e(\tau) d\tau \qquad (1)$$

where u(t) is the manipulated value; *Kp* is the proportional gain and *Ki* is the integral gain; and *e(τ)* is the error between the set-point value and the process value. The controller was set according to the Cohen-Coon tuning rules [7].

3.2. VAV ventilation settings and Control strategies
Although the VAV system usually supplies the inlet air at a stable temperature, in accordance with the measurements performed in the building, the inlet air temperature can drop down to 18 °C when necessary. In four variants (V2, V5, V7 and V9) the temperature of the inlet air can drop in the case of excessive indoor air temperature (measured in reference zone). In addition, in the variants V2 and V7 the inlet air temperature was decreased during the night setback, when the heater in the air conditioning unit was turned off.

The air change rate during the night was set to 1 h^{-1}, which caused high energy consumption. Night setback of ventilation was therefore implemented, and the ventilation system was turned off between 6:00 PM and 6:00 AM. To use the VAV system also for heating and cooling, the air flow rate was controlled both depending on the CO_2 concentration as well as on the indoor air temperature.

3.3. Shading system settings
Automatically operated blinds are used to reduce overheating in the building. The process variable of the shading system control is the incident solar radiation on the external wall with the glazed component. Moreover, the position of the blinds also depends on the indoor air temperature and the combination of indoor air temperature and incident solar radiation.

3.4. Variants of radiant heating systems and control strategies
The simulations were performed for three heat emission systems (floor heating, thermally active ceiling with pipes embedded in the middle of the concrete core, and thermally active ceiling with pipes embedded near the surface) installed in the building to investigate the effect of different emission systems on thermal comfort (table 2). The optimal control strategy for the ventilation and shading system, variant V8, was used for this comparison.

The floor heating system and the near-surface ceiling system were controlled by a PI controller sensing the room air temperature. However, thermally active building structures may be operated under various control strategies. Therefore, four control strategies were implemented to the simulation model for the thermally active ceiling to examine their influence on the energy demand and thermal comfort: (1) on-off (three-step control) in dependence of the room temperature is one of the simplest method to control thermally active building structures; (2) thermal mass of the slab is loaded with thermal energy at night, and it is emitted to the space during the daytime; (3) loading of the concrete core any time based on the difference between supply and return water temperature [8] – the circulation pump is turned off when the difference drops under the limit.

Table 2. The three heat emission systems studied

Emission system	Area [m^2]	Volume flowrate [l/h]	Pipe spacing [mm]	Pipe dimension [mm]
Floor heating	26.5	190	150	16x1.8
Thermally active ceiling	20	260	150	20x2.3
Near surface active ceiling	14	260	100	14x2.0

3.5. Validation of the simulation model

During one reference week (3-11 December, 2017) the permanent and portable sensors measured all the necessary data needed for validation and calibration of the simulation model. The indoor air temperature in the reference office SO 1 was used as the indicator for validation of the simulation model. As the occupants were using the room over the measurement period, occupation, appliance and lighting operation, and shadings´ positions were also recorded. Figure 2 shows amplitudes of the indoor air temperature obtained from the simulation model and from real measurements. The slight differences between real behaviour of the building and simulation model are mainly due to the weather data and TRNSYS internal calculations. The time step of one hour for the weather data file in EPW format (Energy Plus weather data format) is not able to reflect the rapidly changing solar gains, which can lead to inaccuracies during sudden peaks in the solar gains (2:00 PM – 4:00 PM).

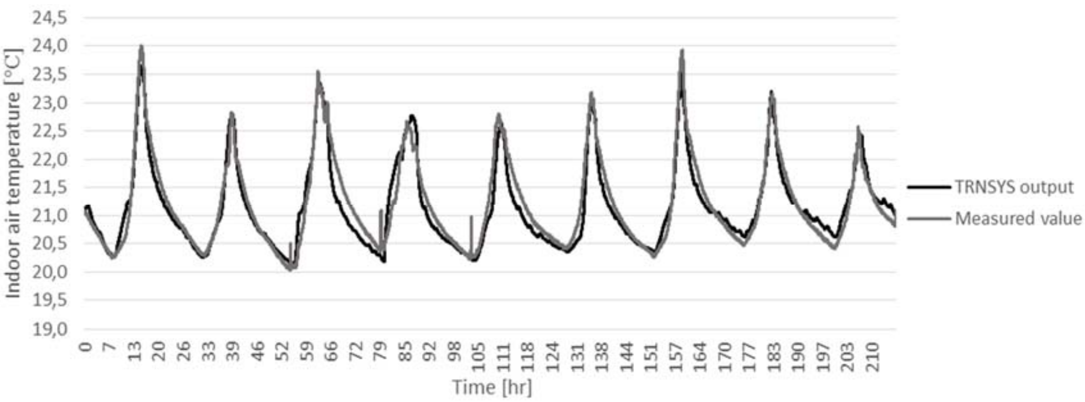

Figure 2. Comparison of simulated and measured air temperature in the reference Single office, SO1, during 3-11 December 2016

3.6. Results

3.6.1. VAV ventilation system. All nine ventilation settings (V1–V9) provided similar thermal comfort during the occupation hours. The indoor air temperature met the criteria as defined in EN 15251 during more than 95 % of the occupied time intervals. During the night, the temperatures drops faster in the variants with no air change, which leads to low indoor air temperatures in the morning. The most stable thermal environment was achieved in the variant V3, however, at the expense of energy efficiency. The variant V8 with ventilation night setback, control of ventilation rate based both on CO_2 concentration and the room air temperature, and floor heating with PI controller, can be considered as the most suitable with respect to the thermal comfort and energy demand.

3.6.2. Shading system. Variant V9 and V10 led to almost the same energy demand and thermal comfort as the optimal variant V8. The effect of different shading control settings is almost negligible. Shading control based on the incident solar radiation on the window is therefore accurate enough to prevent the room sufficiently from overheating.

3.6.3. Radiant heating system. Comparison of the indoor air temperature over 10 days in January is shown in figure 3. Although the results for floor heating (V8) and the near surface thermally active ceiling (V12) are similar, the thermal environment created by the thermally active ceiling (V13) is rather different. The decrease in the air temperature is 1-2 °C lower for the thermally active ceiling (V13) than for the floor heating (V8) due to the smaller heat accumulation capacity of the floor heating system. Over the 10 days simulated, the energy input of the thermally active ceiling was 31 % higher than for the floor heating (figure 4, figure 5). However the accumulation potential of the thermally active elements would probably occur after the time period longer than 10 days. During the reference days in March the indoor air temperature difference was lower, as the ambient temperatures were milder and the values of incident solar radiation higher.

The control variants of thermally active ceiling (V14-V17) are providing good thermal comfort. However, except for the variant V17, the energy inputs were considerably exceeding the value of energy input of the optimal variant V8 (figure 4, figure 5).

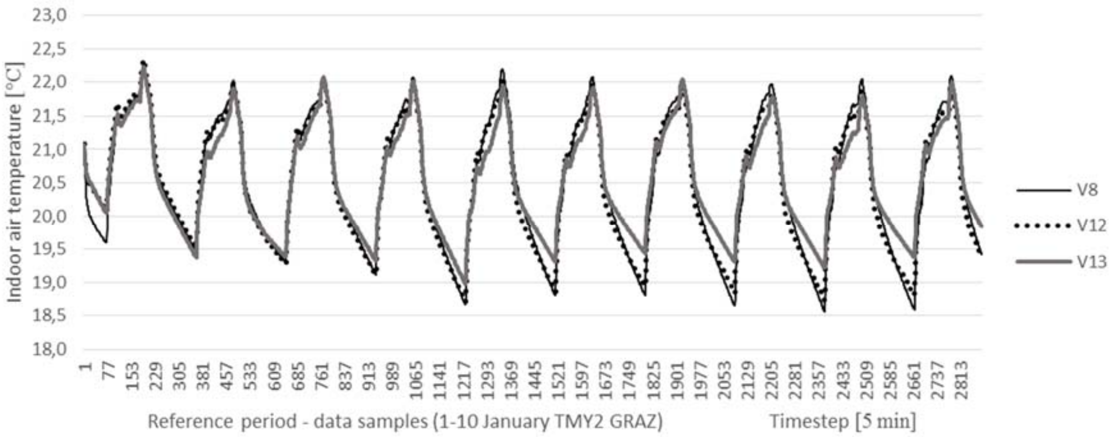

Figure 3. Indoor air temperature created by 3 different radiant heating systems

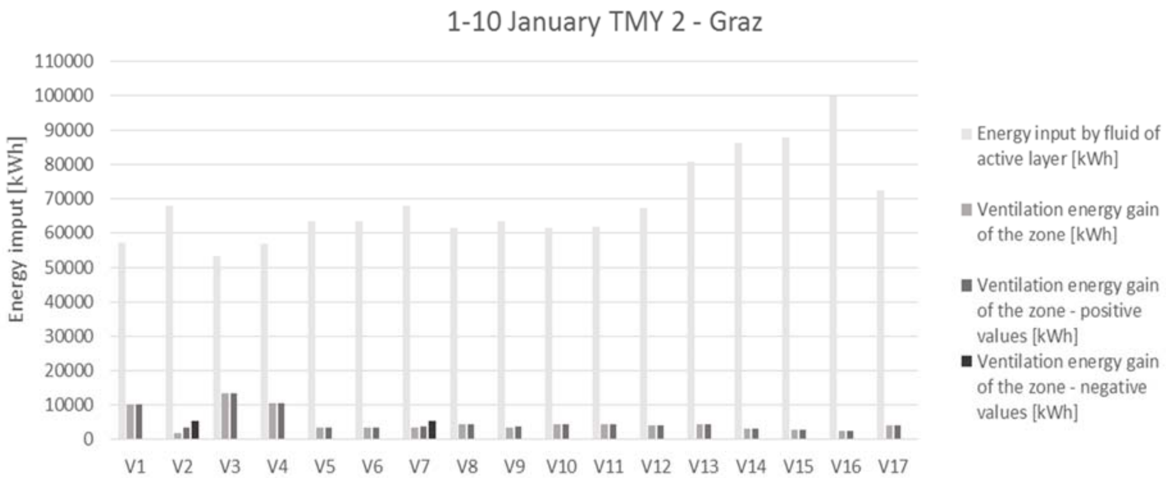

Figure 4. Energy inputs and gains by the ventilation system and heating systems in January – 17 variants

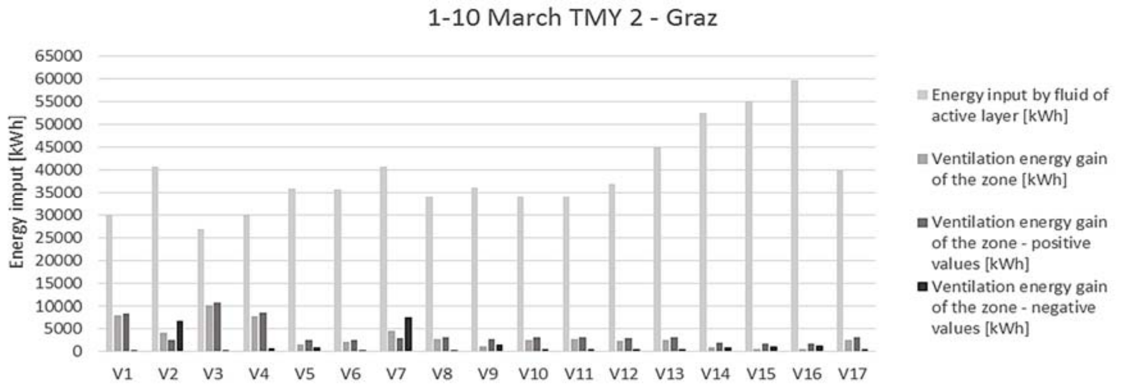

Figure 5. Energy inputs and gains by the ventilation system and heating systems in March–17 variants

4. Conclusion

The results have shown that the application of thermally active ceiling in an office building may not be the optimal solution in case that the building is not continuously operated. In such a case, space heating by a thermally active building element can lead to excessive energy consumption during the unoccupied time intervals. However, the thermally active element can be capable of creating thermal comfort at favourable energy demand when combined with a floor heating system. It was also found that the effect of night ventilation setback on the energy demand is considerable. The energy demand can be further decreased by lowering the air change rate, rather than lowering the inlet air temperature of the VAV ventilation system.

Acknowledgement

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