Solving the Thermal Comfort Challenges in a New-Type Office Building – Case Study

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Abstract

This study evaluates the potential of thermal comfort enhancement in selected zones of a modern office building with high ratio of glazed façade and a heating / cooling system with high thermal inertia. Experimental measurements were performed over three reference weeks, distributed uniformly over heating, transition and cooling period. Results of the measurements indicate overheating during 5 % to 30 % time depending on the evaluated time interval. Subsequently, a simulation model was created to help investigate the possibilities to eliminate the problems with thermal comfort. The simulations indicate a potential to enhance thermal comfort by improving the control strategy for heating, ventilation and external blinds.

Introduction

The recent trend to design buildings with high ratio of glazed areas is mainly initiated by architects to provide more daylight and a modern attractive look for public and for the potential users. However, these buildings 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 (Carmody et al., 2004). 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 (Brunner et al., 2001). 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. This is important in buildings with a centralised heating and ventilation system, where some parts of the buildings should be heated and some cooled at the same time. To maintain comfortable indoor environment in building sections with direct sunlight, operation of windows with shading elements and low solar heat gain coefficient (SHGC) is necessary. However, in practice a compromise may be needed between protecting the building from unwanted solar gains and providing enough daylight to the occupants.

The lightweight glazed envelopes have been traditionally combined with convective all-air or fancoil heating and cooling systems. As opposed to these convective systems, recently the number of radiant system installations has been increasing 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 (Olesen, 2002; Babjak et al., 2007) and a uniform air distribution, close to complete mixing (Krajcik et al., 2012; Tomasi et al., 2013) 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.

Aims, objectives and approach

The present study is focused on the indoor environment in a newly built office building with high ratio of glazed façade and a heating / cooling system with high thermal inertia, in particular on the problems with thermal discomfort. The main aim is to evaluate the potential of thermal comfort enhancement in the selected reference zone by improving the control strategy for heating, ventilation and external blinds. The particular objectives are:

a) Evaluate thermal comfort by experimental measurements and define the problems.

b) Create a validated simulation model.

c) Compare three different radiant systems in terms of thermal comfort and energy performance with emphasize on heating.

d) Optimize the shading and ventilation control strategy with emphasize on heating.

The study is divided into two phases: the first phase includes experimental measurements to reveal the potential problems with thermal discomfort and to provide data for computer model validation, whereas the second phase is focused on optimization of the thermal environment by computer simulations.

Description of the experimental object

The experimental measurements, 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. This allows performing field research of various systems at well-defined and well-monitored boundary conditions, contrary to the typical situation, when the research is performed either in field conditions with very limited possibility of control, or at laboratory conditions which are well-defined, but often too "artificial".

b) The building includes three different types of radiant systems that can be run individually or simultaneously, mechanical ventilation, external blinds, three different types of heat withdrawal systems (helix probes, flat collector, and energy baskets) which can be combined with innovative types of heat pumps (acoustic heat pumps, heat pumps using the Peltier effect), etc. It is possible to combine the technologies and run them under various control strategies defined by the investigator.

This building thus allows designing experiments to investigate the effects of real user behaviour 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.

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.

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 (Fig. 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.

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.

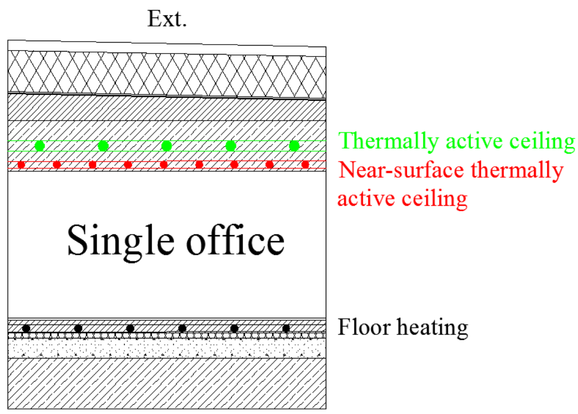

Figure 1: Position of three radiant systems regarding to Single office 1

Indoor environment assessment and problems definition

Methodology and measuring instruments

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.

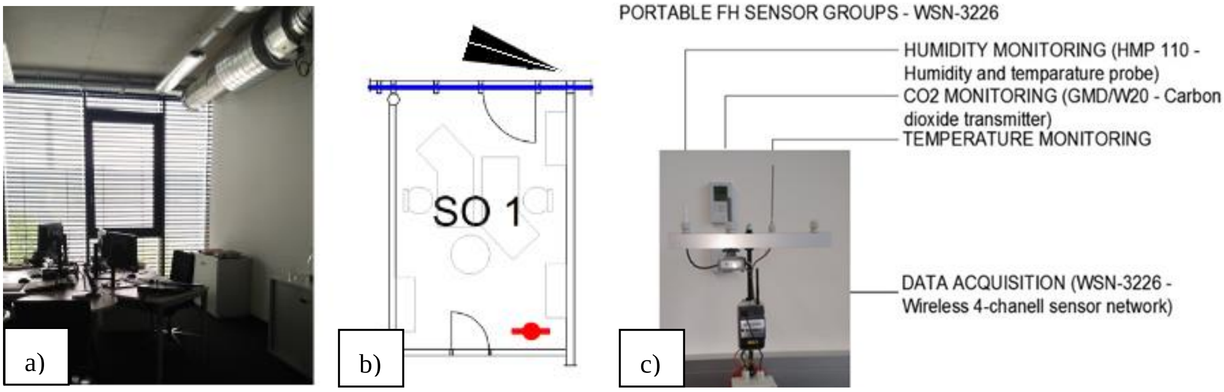

Figure 2: a) Single office 1/1, b) Portable sensor group location in Single office 1, c) Portable sensor group.

The monitored indoor environment indicators measured by the portable monitoring devices were: air temperature, relative humidity and carbon dioxide concentration. The portable stands were installed in six permanently occupied offices in 2016.

Besides, energy consumption meters and other instruments monitoring the relevant properties of the HVAC systems, and a weather station measuring ambient conditions were also installed. In summary, the three groups of measuring instruments installed were:

- Energy consumption meters and HVAC sensors monitoring temperatures and flow rates – in the engine room;
- Portable stands with sensors monitoring indoor air temperature, humidity and CO_2 concentration – in selected offices;
- Weather station with sensors monitoring ambient air temperature and humidity – on the roof.

Single office 1 (SO 1) has been selected as the reference room with regard to its thermal stability. Fig. 2 shows photograph of the room, portable measuring device, and location of the sensor in the reference room SO 1.

The time samples were collected over three reference weeks in 2016 and the data outside the working hours (6:00 PM - 6:00 AM) were filtered out. The indoor environment was evaluated as defined in the European standard EN 15251.

Results and discussion of the experimental measurements

A room can be classified into one of the four categories of the indoor environment as defined in EN 15251. The nominal level of expectations for new and renovated buildings is represented by category II (20 - 24 °C for heating, 23 - 26 °C for cooling). Category IV should be accepted for only very limited time. Fig. 3 shows results of the air temperature measurements during three reference weeks and classification of the reference room SO 1 into the four categories of thermal comfort (I to IV). 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).

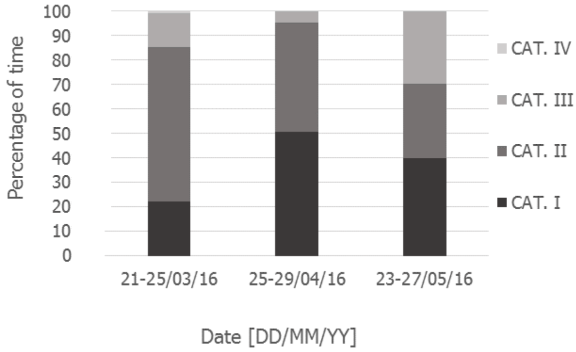

Figure 3: Classification of thermal environment into four categories as defined in EN 15251.

The curves in Fig. 4 represent amplitudes of the indoor air temperature in the reference office SO 1 monitored 21-25 March 2016 (heating period) and 23-27 May 2016 (cooling period). Generally, the temperature is above the recommended limit during heating period and below the limit during cooling period. 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.

The indoor air temperature peaks during the afternoon as the consequence of high ratio of glazed components, solar gains and low heat loss. The thermal environment in the room was also influenced by the occupants´ behaviour, as the automatic shading system was not in operation and the positions of the blinds were adjusted manually according to users´ preferences. As the building is still in trial operation, elimination of the existing problems is one of the main research tasks. A suitable tool to achieve this can be automatized shading control with respect to the operation of HVAC systems.

The relative air humidity was satisfactory (cat. I) more than 95 % of the time during the heating and transition period. As adiabatic cooling is installed in the air conditioning unit, higher values of relative humidity can occur during the days with higher ambient temperature and cooling demand. The indoor air quality was expressed as the amount of indoor CO_2 concentration above the outdoor concentration.

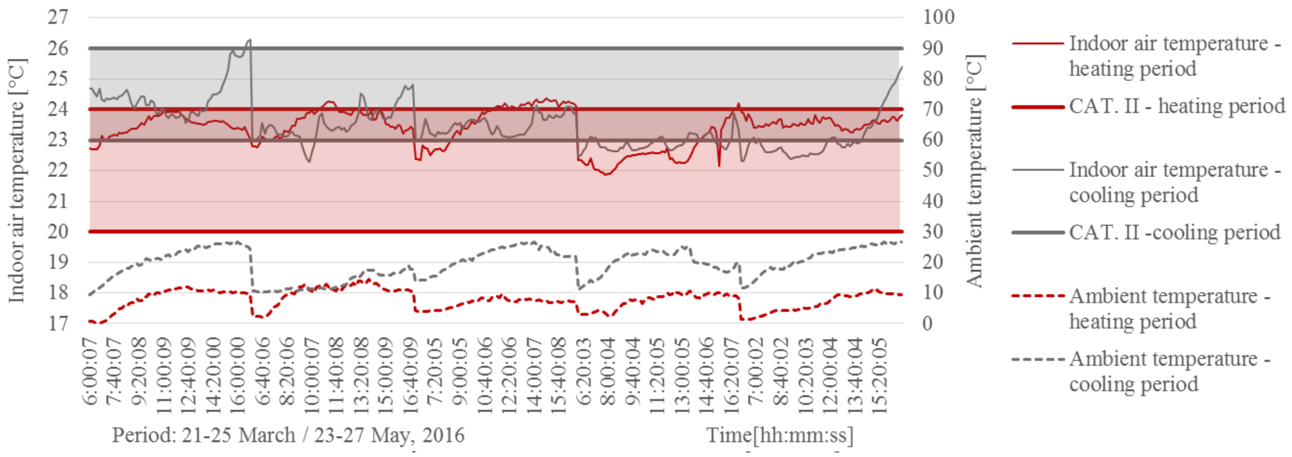

Figure 4: Air temperature in Single office 1 during occupied time intervals in heating and cooling period.

The indoor air quality in all monitored areas over the entire monitoring period met the criteria as defined in EN 15251 (350 ppm above the outside concentration – cat. I.).

Simulation of the reference room and thermal comfort enhancement

Computer simulations of the reference room SO 1 were performed to examine the possibilities of overheating reduction. The problems with thermal comfort in cooling period, when the indoor air temperature is generally lower than required by the standard, is caused by low room air temperature set-point. This deficiency can be addressed by optimization of set-point temperatures in the automation and control system. To investigate the possible improvements in shading and HVAC operation in winter, one reference week within the heating period was selected. The presented simulation model was developed within TRNSYS environment due to its feasibility for transient simulations of HVAC systems.

HVAC systems 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 inlet temperature is maintained by a three-way mixing valve. 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 16 °C during the night by adjusting the inlet temperature of the floor heating. 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; K_p is the proportional gain and K_i is the integral gain; and $e(\tau)$ is the error between the set-point value and the process value. The controller was set according to the Cohen-Coon tuning rules (O'Dwyer, 2003).

The fresh air change of 4 h^{-1} was provided by ventilation system. The inlet air temperature varied ranging between 17 °C and 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:

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

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).

The shading system represented by external blinds with 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.

Influence of shading and ventilation temperature control on thermal comfort

Four variants (Tab. 1) were implemented to examine the influence of shading and ventilation temperature control on thermal comfort.

Table 1: The four investigated variants (V1-V4).

Variant	V1	V2	V3	V4
Shading system operation	On	Off	On	Off
Ventilation inlet temperature	17-22°C	17-22°C	22°C	22°C

The blinds position was adjusted depending on the amount of incident solar radiation on the external wall. Reaching the solar radiation value of 600 kJ/h.m^2 causes that the blinds fully cover the window, which results to 80 % reflection of the solar radiation. Otherwise, the shading covers 30 % of the window area. The ventilation system is set to 22 °C, however, when the blinds are not capable to sufficiently block solar radiation the inlet temperature can be proportionally lowered to 17 °C. During the night, the temperature set-points and air change rates are decreased (night setback).

Comparison of the three radiant systems

The simulations were performed for the three heat/cool emission systems (thermally active core with pipes embedded in the middle of the concrete ceiling, thermally active core with pipes embedded near the ceiling surface, and floor heating) installed in the building to investigate the effect of different emission systems on thermal comfort (Tab. 2). The control strategies and set points described in the variant V1 (Tab. 1) were used for this comparison.

Table 2: Parameters of the three heat emission systems

Emission system	Area [m2]	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

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. 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´ position were also recorded. Fig. 5 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 solar gains (2:00 PM – 4:00 PM).

The oscillations in the indoor air temperature are caused by high air change rates (up to 4 h^{-1}) and internal estimations of the program calculating mixing of zone air.

Results and discussion of computer simulations

The indoor air temperature and the corresponding values of solar radiation during heating period are shown in Fig. 6. During the first simulated day with low level of solar radiation, the indoor air temperature is at about the same level for all variants, regardless if the blinds are fully open or closed. This is in agreement with the results of physical measurements during overcast days. However, during the next simulated days with higher solar radiation, the indoor air temperature is rapidly changing, and the temperature difference between the variants V1 and V2 is reaching over 5 °C. These results indicate the important effect of automation and shading control on thermal balance of the building. When the blinds are not in operation, the air temperature in variants V2 and V4 exceeds 26 °C even during days with ambient temperature below 10 °C, causing thermal discomfort. Least favourable results were obtained for the variant V4, when the blinds were not in operation and the inlet air temperature was kept constant at 22 °C; in this case thermal comfort was outside cat. II during 26 % of time. In the variant V2 the negative effect of excessive solar gains is partially counterbalanced by the cooling effect of the cold ventilation air. The results of indoor air temperature are most favourable for variants V1 and V3 when the blinds are in operation; in this case the room air temperature during the occupied hours is always kept near the desired 22 °C, and thermal comfort is within cat. II during more than 90 % of time. Best results were achieved for the variant V1, when the blinds are in operation and the inlet air temperature is allowed to drop down to 17 °C when needed.

The operation parameters for the three simulated radiant systems shown in Fig. 7 and the indoor air temperatures shown in Fig. 8 indicate that the inlet temperature, pump operation cycles and thermal environment are very similar for all three emission systems.

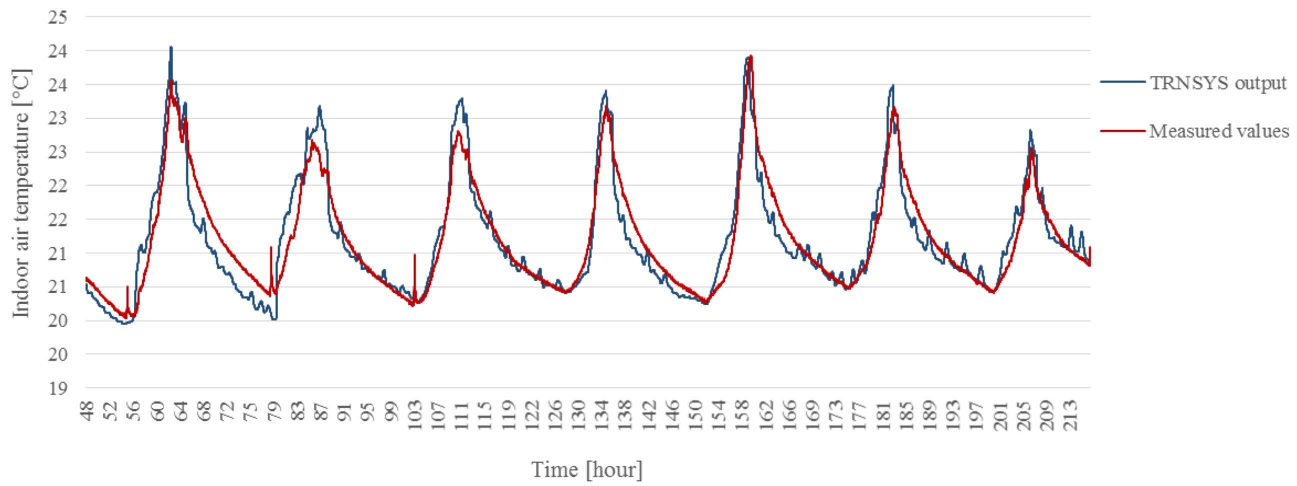

Figure 5: Comparison of simulated and measured air temperature in Single office during 3-11 December 2016.

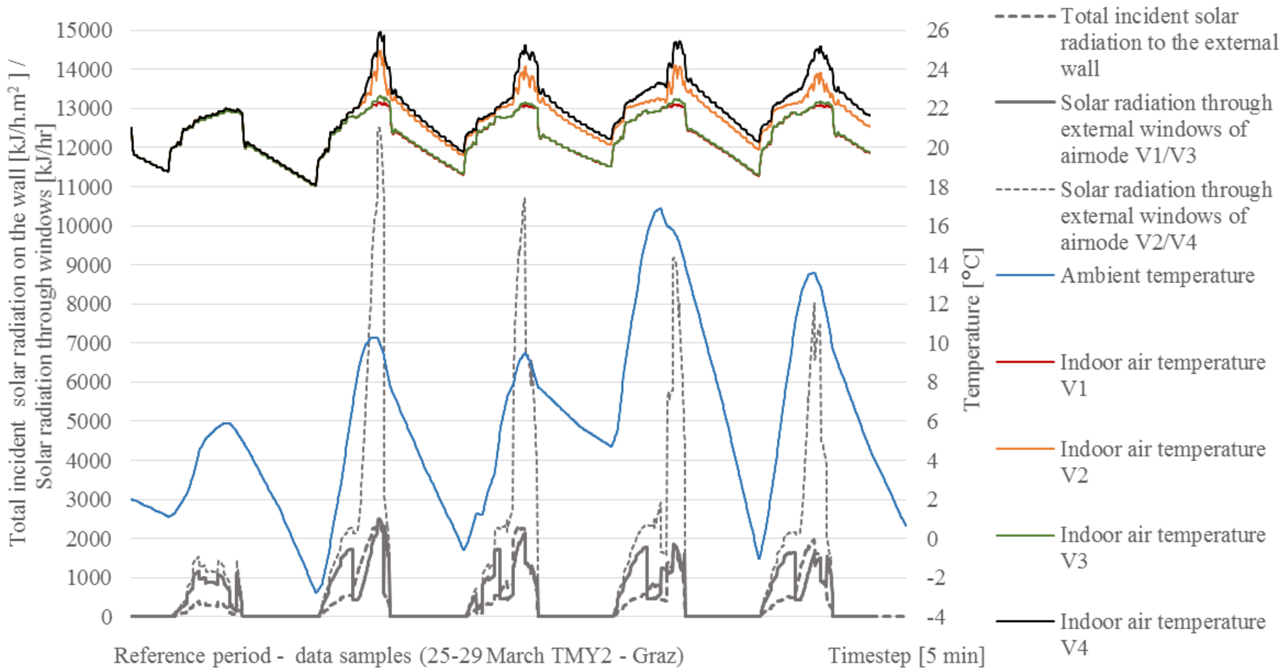

Figure 6: TRNSYS floor heating output – indoor air temperatures and solar radiation profiles (four set-point variants).

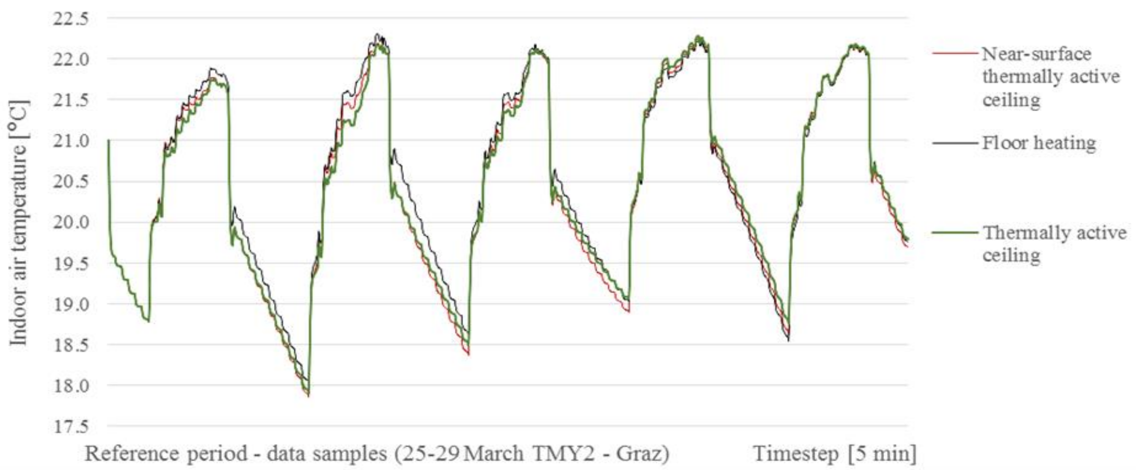

Figure 7: TRNSYS output – comparison of indoor air temperatures created by the three simulated radiant systems.

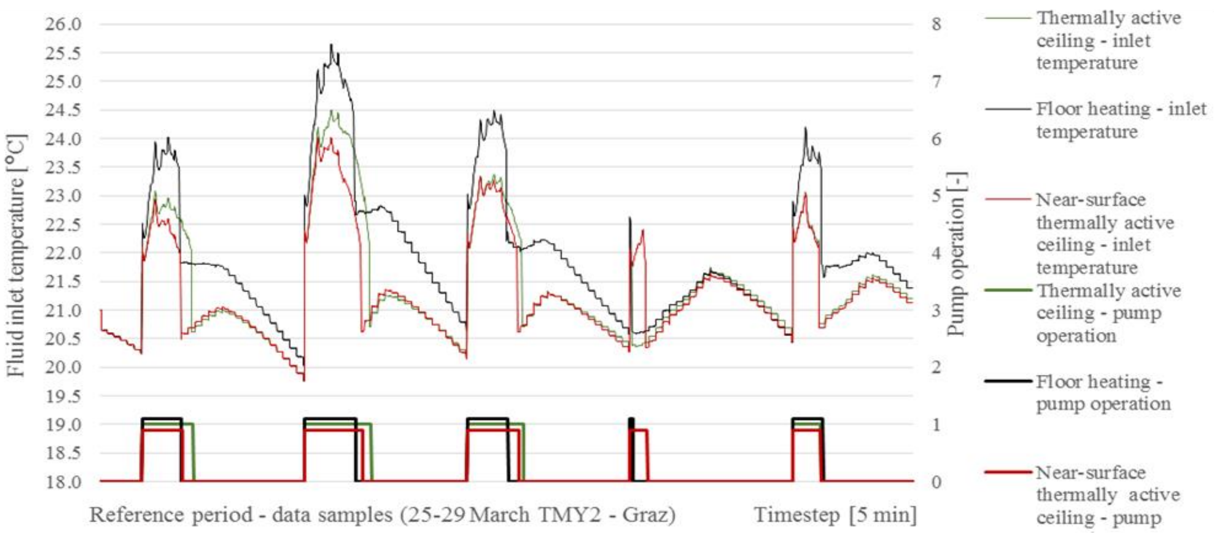

Figure 8: TRNSYS output – operation parameters of the three simulated radiant systems.

Thus, for the most favourable variant V1 all simulated emission systems are capable of creating comfortable thermal environment despite of the high thermal inertia of the accumulated concrete core. The energy consumption was almost identical for floor heating and near-surface thermally active ceiling, whereas it was 23 % higher for thermally active ceiling with pipes in the middle of the concrete core than for the other two systems.

Conclusion

The physical measurement revealed problems with thermal discomfort due to overheating in heating period and overcooling in cooling period. The problems with overcooling can be solved by properly adjusting the room air set-point temperature. The uncomfortably high room air temperature in winter was caused by excessive solar heat gains through the large glazed areas of the facade, and partially by the slow reaction of the emission systems with high accumulation capacity on changes in thermal balance. The computer simulations indicate that the problems can be eliminated and a comfortable thermal environment can be created in winter by: a) proper control strategy of the heating system with high thermal inertia, b) proper automated control of the external blinds and ventilation temperature; enhanced blinds and inlet air temperature control led to about 20 % reduction of time outside the recommended limit as compared to the alternative with no blinds and constant inlet air temperature.

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