THERMAL COMFORT AND ENERGY CONSUMPTION USING DIFFERENT RADIANT HEATING/COOLING SYSTEMS IN A MODERN OFFICE BUILDING

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Abstract

The aim of the study is to evaluate the potential of enhancing thermal comfort and energy consumption created by three different radiant systems in the newly-built Energetikum office building. A representative office, Simulation room 1/1, was selected from 6 areas equipped with portable sensor groups for the indoor environment monitoring. The presented data obtained from 3 reference weeks; the heating, transition and cooling periods indicate overheating, particularly during the heating and transition period. The values of the indoor air temperature during the heating and transition period could not meet the normative criteria according to standard EN 15251:2007 (cat. II.) for 15-30% of the time intervals evaluated. Consequently, a simulation model of the selected office was created and points to the possibilities of improving the control system, which can lead to an elimination of the problem with overheating. Three different radiant systems – floor heating/cooling, a thermally active ceiling, and a near-surface thermally active ceiling were implemented in the model. A comparison of their effects on thermal comfort and energy consumption is presented in the paper.

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Key words

- Thermal comfort,
- Glazed envelope,
- Overheating,
- Simulation.

1 INTRODUCTION

Environmental comfort in offices ought to provide optimal conditions for the efficient productivity of the occupants. However, a recent trend in construction, i.e., light-weight facades with a high portion of glazed components in combination with radiant heating/cooling systems, reveals extensive thermal comfort issues. With regard to the fact that lightweight glazed facades are very sensitive to climatic conditions, a properly designed combination of HVAC, lightning, and solar shading set-points is crucial for energy performance. The research is focused on the environmental behaviour of a newly-built office building, particularly on a problem with thermal discomfort.

2 A MODERN OFFICE BUILDING WITH LARGE GLAZED AREAS

Large glazed areas are always related to higher energy losses during the heating season and to the overheating of indoor spaces because of the direct sun (Brunner et. al, 2001). During the summer problems with interior overheating are expected; however, cold days with a high amount of solar irradiation, when the solar gains exceed the energy demands for the heating, are a crucial area of HVAC design. This problem is very significant 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. However, to protect the building from unwanted solar gains (by an automatically

controlled shading system), a compromise between the day lighting and solar gains has to be achieved.

Research on people's performance while working under different thermal conditions showed results indicating lower performance during uncomfortable air temperature periods (Šeduikyte and Paukštys, 2008). According to (Niemi et al., 2002), employees' performance decreased by 2.2% by every 1 °C over 25 °C. Other research in an office building showed a decrease in performance of 15% when the temperature increased from 24.8 °C to 26 °C (Feder-spiel et al., 2002).

As there is indisputable pressure on the energy efficiency of buildings, low-exergy radiant systems are being implemented in building technology. Radiant heating systems are very suitable combined with renewable energy sources, e.g., heat pumps and solar collectors. The external weather conditions, solar irradiance, changes in internal heat gains, and the small heat accumulation capability of a light-weight facade can result in relatively dynamic changes in the thermal balance of a building. Due to the high time constant, i.e., the slow reactions of radiant heating/cooling systems, it may not be able to respond to these changes fast enough to assure a comfortable thermal environment, which can lead in naturally ventilated buildings to temperatures as high as 29.5 °C (Nemethova et al., 2016a).

3 DESCRIPTION OF THE REFERENCE OBJECT AND ZONE

Due to the lack of suitable currently constructed experimental buildings, an interdisciplinary living laboratory, the Energetikum, was designed. An investigation of an indoor environment as a result of a properly designed control of HVAC systems and other building technology, was one of the main purposes of the project. Simulation room 1/1, which is located in the building, has been used as an office for the employees of Research Burgenland GmbH since April 2015.

3.1 Building envelope, construction and thermal properties

The two-storey building, which is located in Pinkafeld, Austria, has two types of façade to eliminate higher heating demands during the winter and provide the best conditions for the infiltration of natural lighting. Opaque surfaces constitute 82 percent of the envelope, and the light-weight components or windows constitute 18 percent (orientated to the W-S-W and S-S-E). All the transparent parts of the façade have a triple glazing with a thermal transmittance value between 0.79 and 1.10 W/(m².K). The Simulation Room, with its fully

glazed envelope oriented to the west-south-west, is located on the second floor of the building. The office, with a floor area of 26.4 m², is regularly occupied by 2 employees.

3.2 Description of the HVAC systems installed

A brine/water heat pump was installed to supply the whole Energetikum structure with heat. The area available for geothermal energy is too low to cover the power supply created by the heat pump. Therefore, an additional energy source, a gas boiler, was installed. Three separate distribution systems have been implemented for the heating/cooling system (Fig. 1). The systems can run simultaneously or separately, depending on the current demands. The structure is mechanically ventilated and provides complex air conditioning. The air exchange is fully covered by mechanical ventilation; the window openings are not essential to maintain the minimal air change rates.

Fig. 1 Heating and cooling systems - Simulation room 1/1

4 ASSESSMENT OF THERMAL COMFORT AND DETERMINATION OF THE CRITICAL AREAS

For monitoring the various indoor environmental indicators such as the air temperature, relative humidity, and concentration of carbon dioxide, portable sensor groups were installed in six selected offices in 2016. Energy consumption sensors, sensors measuring the heating and ventilation system properties, and a weather station measuring the ambient conditions were simultaneously installed. Based on the recorded data, it is possible to evaluate the indoor environmental quality, energy consumption, and behaviour of the HVAC systems.

PORTABLE FH SENSOR GROUPS - WSN-3226

Fig. 2 Portable monitoring technology – Simulation room 1/1

Fig. 3 Classification of thermal environment into 4 categories in accordance with EN 15251 - Simulation Room 1/1

4.1 Monitoring the thermal comfort and technology installed

Besides the pre-installed SIEMENS sensors, which are aimed at the HVAC operation and control, portable “monitoring-trees” with highly sensitive sensors were installed. These help to detect problems with the indoor environment and energy consumption. There is a potential for energy-saving improvements via applications of different control strategies to the system.

4.2 Results and observations

Time samples were collected during three reference weeks during year (2016), and the data was sorted according to the working hours (6:00 AM - 6:00 PM) and assessed in accordance with EN 15251:2007.

According to EN 15251, the room can be classified in one of four indoor environment categories. 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). The results of the air temperature and classification in the four categories of thermal comfort are shown in Fig. 3. Category IV can be tolerated for only a very limited time period. The results indicate that the desired thermal environment was achieved for only a limited period of time, which was mostly due to the excessive air temperature. According to Fig. 3, the thermal environment in the building suffers from thermal discomfort during all three periods. Overheating mainly occurs in the transition and heating period; during the cooling period, the discomfort is mainly caused by temperatures below the values required by the standard.

The temperature curves in Fig. 4 represent the amplitudes of the indoor air temperature in the reference offices. Generally, the temperature range is above the desired range during the heating period and below the desired area during the cooling period, which suggests that the control system is not considering an adaptive principle. By adjusting the set temperatures or control settings (e.g., the PI controller, shading devices, flow rates), it would be possible to save a significant amount of energy simultaneously while enhancing the thermal comfort.

The peak of overheating occurs during the afternoon, as a consequence of the solar gain accumulation and low heat losses. However, as the automatic shading system was not operating during the time periods evaluated, the behaviour of the occupants strongly influenced the thermal conditions in the corresponding offices (opening windows, the shading control). With regard to the fact that the building is still in a trial operation, the building's operation is being observed to find the most suitable solutions for the issues raised. Consequently,

Fig. 4 Comparison of indoor air temperatures in the reference office during the occupied time intervals of the 3 periods evaluated

different control strategies for the HVAC systems should be considered, which will create a challenge for further study and research.

5 SIMULATION OF BUILDING PERFORMANCE – ENERGY CONSUMPTION AND THERMAL COMFORT

As a tool for examining the possibility of reducing the overheating, the simulation of a reference room located in the structure was undertaken. Simulation room 1 was selected because of its orientation and because a portion of the glazed areas was convenient for the experiment. As the problem with the thermal comfort during the cooling period (temperatures lower than that required by the standards), which is caused by the low set-point temperatures of the cooling system, can be quite easily reduced, the reference week from the heating period was chosen for the study. The model presented was developed within a TRNSYS environment.

5.1 HVAC systems control and set-points

A system of 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 inlet temperature was maintained at the desired value by a three-way mixing valve. A PI controlling algorithm was applied to minimize the temperature fluctuations at around 21 °C during the occupied time periods and 16 °C during the night by adjusting the inlet flow rate temperature of the radiant heating.

Normative air change 4 [1/h] is provided by the ventilation system. The inlet air temperature varies and ranges between 17 °C and 22 °C. The air change rate is controlled by a three stage controller, depending on the CO₂ concentration of the indoor air. The temperature of the inlet is controlled proportionally, depending on the amount of solar radiation.

A system of blinds with 80% impenetrability protects the room from any redundant solar gains. The room occupation, lightning system, and installed equipment are also integrated into the model.

Four set-point variations were selected to examine the effect of the shading and ventilation system on the thermal comfort (Tab. 1). The position of the blinds was assigned according to the amount of incident solar radiation on the external wall. An excessive solar radiation value of 600 kJ/h.m² causes the blinds to fully cover the window, which results in a reflection of 80% of the solar radiation. Otherwise, the shading covers 30% of the window area. The ventilation system is set to a temperature of 21 °C. However, when the blinds system is not capable of covering the solar radiation, the tem-

perature can be proportionally lowered to 17 °C. During the night, the temperatures and air change rates decrease, according to the night setback (Nemethova et. al, 2016b).

Tab. 1 Set-point comparison – 4 variations

	Variation 1	Variation 2	Variation 3	Variation 4
Shading system operation	On (30/100%)	Off	On (30/100%)	Off
Ventilation inlet temperatures	17-22°C	17-22°C	22°C	22°C

The indoor air temperature and the corresponding values of the solar radiation during the heating period are shown in Fig. 5. During the first simulated day with a low level of solar radiation, the indoor air temperature was at about the same level for all the variants, regardless of whether the blinds are fully open or closed. This is in agreement with the results of the physical measurements during overcast days. However, during the subsequent simulated days with higher solar radiation, the indoor air temperature rapidly changed, and the difference in temperature between variants V1 and V2 reached over 5 °C. These results indicate the important effect of automation and shading control on the thermal balance of the building. When the blinds were not in operation, the air temperature in variants V2 and V4 exceeded 26 °C even during days with an ambient temperature below 10 °C, which causes thermal discomfort. The least favourable results were obtained for variant V4, when the blinds were not in operation, and the inlet air temperature was kept constant at 22 °C; in this case the

thermal comfort was outside category II around 26% of the time. In variant V2 the negative effect of any excessive solar gains is partially counterbalanced by the cooling effect of the cold ventilated air. The results of the 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 the thermal comfort is within category II more than 90% of the time. The best results were achieved for variant V1, when the blinds are in operation, and the inlet air temperature is allowed to drop down to 17 °C when needed (Nemethova et. al, 2016b).

5.2 Comparison of the three radiant systems

The simulations were performed for the three heat/cool emission systems (a thermally active core with pipes embedded in the middle of a concrete ceiling, a thermally active core with pipes embedded near the ceiling's 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 variant V1 (Tab. 1) were used for this comparison.

The parameters of operation for the three simulated radiant systems shown in Fig. 6 and the indoor air temperatures shown in Fig. 7 indicate that the inlet temperature, pump operation cycles, and thermal environment are very similar for all three emission systems.

Thus, for the most favourable variant V1, all the simulated emission systems are capable of creating a comfortable thermal environment despite the high thermal inertia of the accumulated concrete

Tab. 2 Parameters of the three radiant systems

Radiant system type	Effective area [m ²]	Volume flow rate [l/h]	Pipe spacing [mm]	Pipe dimension [mm]
Floor heating / cooling	26.5	190	150	16x1.8
Thermally active ceiling	20	280	150	20x2.3
Near-surface thermally active ceiling	14	270	100	14x2.0

Fig. 5 TRNSYS output – indoor air temperatures and solar radiation profiles (four set-point variants) while using the floor heating system, ventilation and shading

Fig. 6 TRNSYS output – comparison of indoor air temperatures created by the three simulated radiant systems

Fig. 7 TRNSYS output – operation parameters of the three simulated radiant systems

core. The energy consumption was almost identical for the floor heating and the near-surface thermally active ceiling, whereas it was 23% higher for the thermally active ceiling with pipes in the middle of the concrete core than for the other two systems.

6 CONCLUSION

The physical measurements revealed problems with thermal discomfort due to overheating in the heating period and overcooling in the cooling period. The problems with overcooling can be solved by properly adjusting the room's air set-point temperature. The uncomfortably high room air temperature in the winter was caused by excessive solar heat gains through the large glazed areas of the façade, and also partially by the slow reaction of the emission systems with the high accumulation capacity for changes in the thermal balance. The computer simulations indicate that the problems can be eliminated and that a comfortable thermal environment can be created in the winter by: a) a proper control strategy of the heating system with high thermal inertia, b) a proper automated control of the external blinds and ventilation temperature. The enhanced blinds and inlet air

temperature control led to about a 20% reduction of the time outside the recommended limit as compared to the alternative with no blinds and a constant inlet air temperature. However, the influence of the radiant heating / cooling system type is negligible in comparison with the proper control setting of the system.

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