DOI: 10.14256/JCE.1289.2015

Građevinar 2/2016

Primljen / Received: 3.3.2015.
Ispravljen / Corrected: 5.6.2015.
Prihvaćen / Accepted: 25.8.2015.
Dostupno online / Available online: 10.3.2016.

Indoor environment in retrofitted offices equipped with radiant ceiling panels

Authors:

[1]Sabina Jordan, MSc. Arh.
sabina.jordan@zag.si

[1] Jože Hafner, PhD Mech.
joze.hafner@zag.si

[2]Tilmann E. Kuhn, MPhys.
tilmann.kuhn@ise.fraunhofer.de

[1]Prof. Andraž Legat, PhD Phys.
andraz.legat@zag.si

[3]Prof. Martina Zbašnik-Senegačnik, PhD. Arh.
martina.zbasnik@fa.uni-lj.si

[1]Slovenian National Building and Civil Engineering Institute
[2]Fraunhofer Institute for Solar Energy Systems
[3]University of Ljubljana, Faculty of Architecture

Subject review

Sabina Jordan, Jože Hafner, Tilmann E. Kuhn, Andraž Legat, Martina Zbašnik-Senegačnik

Indoor environment in retrofitted offices equipped with radiant ceiling panels

The indoor environment in retrofitted pilot demonstration offices, equipped with advanced radiant ceiling panels that were used for heating and cooling, is evaluated in the paper. Comprehensive analyses based on various sets of real case measurements were carried out in order to assess the efficiency and adequacy of the proposed retrofitting concept. It was established that the entire system for tempering the offices operates well, and that the range of indoor air temperatures ensures the highest level of comfort.

Key words:
analysis, evaluation, retrofitting concept, radiant ceiling panels, heating and cooling

Pregledni rad

Sabina Jordan, Jože Hafner, Tilmann E. Kuhn, Andraž Legat, Martina Zbašnik-Senegačnik

Unutarnja okolina renoviranih ureda opremljenih stropnim isijavajućim pločama

U radu se ocjenjuje unutarnja okolina renoviranih ureda koji su, kao pokusni primjer, opremljeni naprednim stropnim isijavajućim pločama koje se primjenjuju za grijanje i hlađenje. Obavljene su opsežne analize na bazi raznih nizova stvarnih mjerenja kako bi se ocijenila djelotvornost i prikladnost predložene koncepcije za adaptiranje prostora. Ustanovljeno je da čitav sustav za temperiranje uredskih prostora funkcionira na prikladan način, te da raspon unutarnjih temperatura zraka omogućava postizanje najviše razine udobnosti.

Ključne riječi:
analiza, ocjena, koncept adaptacije, stropne isijavajuće ploče, grijanje i hlađenje

Übersichtsarbeit

Sabina Jordan, Jože Hafner, Tilmann E. Kuhn, Andraž Legat, Martina Zbašnik-Senegačnik

Innenraumklima mit Deckenstrahlplatten ausgestatteter renovierter Büroräume

In dieser Arbeit wird das Innenraumklima renovierter Büroräume bewertet, die als Testbeispiel mit fortschrittlichen Deckenstrahlplatten zur Heizung und Kühlung ausgestattet sind. Ausführliche Analysen wurden basierend auf einer Reihe verschiedener Messungen durchgeführt, um die Effizienz und Eignung des vorgeschlagenen Konzepts bei der Raumadaptation zu beurteilen. Es wurde festgestellt, dass das gesamte System zur Temperierung der Büroräume angemessen funktioniert und der verfügbare Innentemperaturbereich höchstes Komfortniveau ermöglicht.

Schlüsselwörter:
Analyse, Beurteilung, Adaptationskonzept, Deckenstrahlplatten, Heizung und Kühlung

1. Introduction

It is expected that the implementation of the energy retrofit of the existing building stock will soon become one of main priorities for the European construction sector. The total useful floor area can roughly be estimated to 25 billion m^2 (EU27, Switzerland and Norway) [1]. In addition, the requirements for buildings will become much more stringent by the end of 2020, since all new buildings will have to be nearly zero-energy buildings [2]. Necessary measures will have to be taken in order to ensure retrofitting of the existing buildings. These measures will require retrofit or replacement of each building element or system with significant impact on the energy performance of buildings if this is technically, functionally, and economically feasible. An important target of the measures is the non-residential sector, with an estimated average of specific energy consumption of 280 kWh/m^2, which exceeds by at least 40 % that of the residential sector in countries across Europe [1].

It is believed that effective energy savings in buildings can be achieved through the carefully investigated smart concepts and measures. Such concepts include new efficient technologies and solutions that can be applied to both the envelope and infrastructure of buildings, and can thus greatly contribute to achievement of an optimal indoor thermal comfort. When used in retrofitting processes, these technologies will have to be adaptable to technical limitations of the existing building elements and systems. They will also have to be (to some extent) flexible with regard to climate changes. According to Bonacci study, this could refer more to temperature fluctuations and extreme outdoor temperatures in certain periods of time than to general linear trends of yearly mean increase in air temperature [3].

Large-surface radiant systems have recently become a good alternative for heating and cooling the indoor built environment [4-5]. This technology efficiently uses the principle of small temperature difference between a large radiant surface and its surroundings [5]. It can be integrated into the floor, wall or ceiling structure as the so-called thermally activated building system (TABS), or installed as a part of a suspended floor or ceiling. The thermal comfort and energy consumption of radiant surfaces have been an important topic of several studies described in the literature [4-14]. These studies are mainly based on small-scale experiments or numerical models, and they focus on rather specific questions about radiant ceiling systems. Although many of them are limited to cooling or heating only [4-10], the research is in some cases focused on both aspects [11-14].

It was shown that radiant ceiling panels can efficiently be used for heating and cooling in buildings with a good thermal insulation and low cooling loads [14]. Compared to conventional air-conditioning systems, such panels can create a more comfortable environment with a lower energy consumption [13] and can cope with complex user behaviour [11], as long as good solar protection is provided and implemented in a correct way, and as long as mechanical ventilation of the indoor environment is considered specifically. As shown in the study by Miriel et al. [14], when no additional air treatment for increasing convection is provided, the system may limit possible overheating only to some extent. However, better results are achieved by integrating suitable mechanical ventilation. This increases convective heat transfer and improves time response of the radiant system [9]. Simultaneously, the required size of radiant surfaces can be reduced [9]. Determination of a proper heat transfer coefficient and the cooling capacity of the system is, however, of crucial importance, especially in connection with solar gains [5-7]. Furthermore, apart from the ventilation system, surface temperatures of a room can also have a considerable influence on the efficiency of radiant ceiling systems, so that the latter must be evaluated together with the nearby indoor environment and not as separate HVAC equipment [8, 12, 15].

Despite good performance, the radiant ceiling panel systems are still not widely used in practice. Moreover, the operation and influence of this technology on the indoor environment in the heating mode has not been fully verified. The experience that is being gained with such concepts is of great importance as a means to overcome this lack of knowledge. Getting a step ahead in this respect, a radiant ceiling system was installed as a part of an overall energy retrofit of offices in the main headquarters building of the Slovenian National Building and Civil Engineering Institute (ZAG). Its operation was continuously monitored over a one-year period (January 2013 - December 2013). The pilot demonstration offices were part of a larger demonstration presented within the EU project: COST EFFECTIVE (Resource- and Cost-Effective Integration of Renewables in Existing High-Rise Buildings, 7FP, 2008-2012).

Appropriate experimental and measuring methods were applied in the scope of this research in order to analyse operation of the system installed in the pilot offices. The main objective of the research was to evaluate an advanced radiant heating and cooling ceiling system in retrofitted offices, by focusing on thermal comfort in heating mode. In addition to the analyses of the indoor air temperature performance, the paper also provides analysis of energy consumption in the pilot offices. It should however be mentioned that the study was limited to indoor environment of the offices only. Consequently, the assessment of the energy supply equipment and equipment for office operation, the total use of energy, the ventilation system, and the evaluation of various control strategies, are not considered in the paper.

2. Materials and methods

2.1. Problem description: Pilot demonstration and offices and their retrofit

The subject of the present study are four interconnected offices constituting a part of the upper storey of the ZAG building in Ljubljana, Slovenia. The scheme of the offices is shown in Figure 1. In 2012, the offices were subject to an extensive energy

Table 1. Window area of pilot offices

Window surfaces / Offices	Total façade area [m²]	Total window area [m²]	Fixed window area [m²]	Openable window area [m²]	Window share in façade area [%]	
Office 1	11.1	5.5	4.0	1.5	49.7	
Office 2	20.1	10.1	7.1	3.0	50.4	
Office 3	10.7	5.2	3.6	1.5	48.3	
Office 4	19.7	6.6	4.5	2.2	33.5	
Total	**61.5**	**27.4**	**19.2**	**8.2**	**Average**	**45.5**

renovation with an emphasis on a pilot demonstration of innovative radiative heating/cooling ceiling panels. The retrofit measures comprised energy saving works for enhancing the facade energy efficiency, HVAC installation with ceiling heating/cooling panels and mechanical ventilation with recuperation, upgrades of the energy supply and the electrical system, and installation of a building management system (BMS) with sensors, metering devices, and other supporting equipment for monitoring.

The pilot offices occupied a net floor area of 108 m² and their net volume amounted to about 320 m³. They consisted of four office rooms on the 5th floor of the building with the 15°SW orientation (Figure 1). The entrance office was the Office No. 3 with 19.7 m². Then there were two large offices, Office No. 2 and Office No. 4, with the net floor areas of 36.2 m² and 37.8 m², respectively. The smallest office was the Office No. 1 with 14.4 m². The height of the offices from the floor level to the ceiling slab was about 3.2 m. The structure of the walls was quite diverse in composition, and it included plastered brick walls, lightweight gypsum walls, plastered concrete walls, and the ceiling (Figure 1). Parts of the building structure parallel to the façade are two large load-bearing concrete pillars.

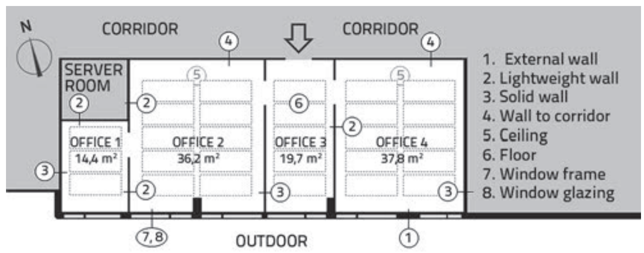

Figure 1. Floor plan of pilot offices with ceiling panels marked with a dashed line, and with main building elements (described in Table 2)

The windows of the offices were large, i.e. they covered almost the entire width of the façade in each office, the exception being the Office No. 4 where one window was smaller. In each office, a part of the window area was fixed, covering roughly 70 % of the total window area. The remaining part of the windows could be opened (Table 1).

Table 2. Description of main building elements

	Building element	Description of improved building elements	U-value [W/m²K]	OLD U-value [W/m²K]
1	External wall (facade)	20 cm concrete wall, 12 cm thermal insulation	0.28	*0.42*
2	Lightweight wall-indoor	2 x 1.25 cm gypsum board, 10 cm thermal insulation	0.34	*0.34*
3	Solid wall-indoor	12 cm brick wall	2.71	*2.71*
4	Wall to corridor-indoor	Combination of 12 cm brick wall and particle boards	1.31	*1.31*
5	Ceiling to unheated attic	20 cm concrete slab, 20 cm thermal insulation	0.18	*0.35*
6	Floor-indoor	20 cm concrete slab, 2 cm thermal insulation, 7 cm screed	1.00	*1.00*
7	Window frame	High insulation aluminium frame	1.6	*1.9*
8	Window glazing	Triple glazing, gas, low-e coatings	0.7	*2.0*
			Overall U-value [W/m²K]	**OLD overall U-value** [W/m²K]
		Structural elements facing external/unheated environment	0.31	*0.60*

In the analysed year 2013, the offices were in full operation; altogether seven people worked in the rooms. There were four occupants in the office No. 2, while offices 1, 3, and 4 each had one occupant. The occupants worked in the offices from Monday till Friday, from 8 a.m. to 5 p.m. Additional energy gains were produced by the use of computers, supporting ICT devices, and lighting.

2.2. Building envelope of pilot offices

Taking into account the existing limitations, all appropriate measures were implemented when retrofitting the old building envelope, initially built in 1982. According to the new concept, reasonably low U-values were needed for the pilot envelope; the existing façade was improved with 4 cm of additional thermal insulation, which gave a total thermal insulation layer 12 cm in thickness. Because of unheated attic space above the pilot offices, the 10 cm thermal insulation of the concrete ceiling slab was improved with an additional 10 cm of thermal insulation. Original double glazed windows were replaced with new high performance window frames and triple glazing with the U-value of 0.70 W/m^{2}K and g-value of 0.29. The description and thermal characteristics of the new building envelope elements are given in Table 2.

During most of the summer, a projecting roof above the façade served as fixed shading for the windows. Nevertheless, new external manually adjustable motorized venetian blinds were installed to enable an effective year-round control of solar radiation. The office occupants used the venetian blinds often; our estimated b value in summer conditions was 0.80. At the inner side of the windows, manually operated roller blinds were mounted in order to protect occupants from glare.

A particular attention was paid to the improvement of the pilot offices envelope by lowering the air exchange rate. After completion of the retrofit, the indoor to outdoor air exchange rate was measured according to the standardized measuring procedure [16] at pressure differences of 50 Pa. The measured value of 1.6h^{-1} is compliant with requirements set by Slovenian legislation, which calls for 2.0 h^{-1} or less for buildings with mechanical ventilation with an air exchange rate greater than 0.7 [17-18]. The measured air exchange rate of the pilot offices can thus be evaluated as very good, taking into account the fact that the pilot offices are a renovation rather than a new building.

2.3. HVAC and control systems of pilot offices

In order to achieve comfortable indoor air temperatures of around 22 °C, the pilot offices were equipped with water-filled ceiling panels for indoor environment heating and cooling. The system was supported by mechanical ventilation, with inlets and outlets at a level close to the ceiling (Figure 2). These locations were chosen because, in the case of displacement ventilation and chilled ceiling applications, it has been shown that, when internal gains are moderately high, the impact of the ceiling surface temperature on the level of mixing and on the magnitude of temperature gradient is of secondary importance [8].

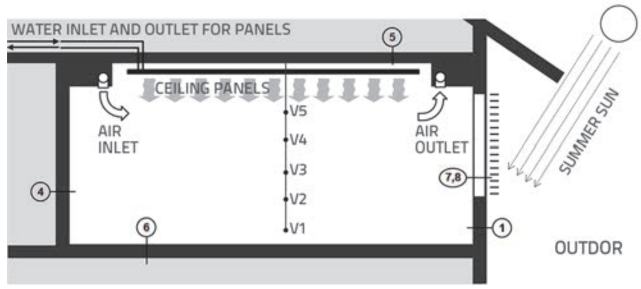

Figure 2. Typical elevation view with main building elements (described in Table 2) showing radiation ceiling panels, air inlets/outlets of mechanical ventilation system, and vertically positioned air temperature sensors (V1-V5)

The energy needed for the heating and cooling of ceiling panels in the pilot offices was provided by the specially designed energy system for the solar energy capturing, transforming and storing (surface area of solar thermal collectors was approximately 30 m^2). The media of the system was water. The heat was stored in a large storage tank (3 m^3) to be used directly for heating the offices when operating in the heating mode. In the cooling mode, the heat was transformed into the cold via an adsorption chiller (8 kW in nominal cooling power) and a cooling tower, and was then stored in a separate storage tank (1 m^3). The natural free cooling for cooling water during the night-time was also used. Two conventional energy backups were predicted for the system in the case of lack of solar energy: the district heating in the heating mode, and the compressor chiller in the cooling mode. The initial operating temperatures for heating and cooling were determined considering the basic geometrical and physical characteristics of the pilot offices: boundary conditions, heating/cooling load, characteristics of the heating/cooling system and supplementary devices, and indoor requirements. The latter were based on parameters such as the allowed room humidity, assumed level of activity of occupants, calculated humidity production per person, and dimensioned air flow rate for ventilation per person.

The panels were designed as large flat plate metal sheets over the copper piping, covering 60 % of each office ceiling slab. The piping was fastened to the ceiling slab with aluminium profiles. All radiant ceiling panels were always operating in the same mode, either heating or cooling the rooms. The product specification was given in W/m^2 per temperature difference (linear function) between an average surface temperature of a panel and an average air temperature in a room. The cooling power was specified as 80-90 W/m^2 per 10 K of temperature difference, whereas the heating power was 60-70 W/m^2 per 10 K of temperature difference. In the pilot offices the temperature difference can reach up to 7K in the cooling mode, and up to 14K in the heating mode. Consequently, the power of the panels in the cooling mode can be as high as 63 W/m^2, while in the heating mode it can raise up to 90 W/m^2.

Operating at relatively low heating temperatures in the heating season, and at relatively high cooling temperatures in the cooling season, this kind of system is considered to be highly energy efficient, and able to provide a good level of thermal comfort. In the heating season, the air temperature of the rooms was set to 22 °C (with local adjustment of ±2 K). The inlet temperature of the water for ceiling panels ranged from 35 °C to 38 °C in the heating mode, while the outlet temperature was by about 5K lower. The air temperature of the rooms was set to 24-25 °C in the cooling season (local adjustment of ±2K at room regulators). The cooling was provided to the offices by cold water in the temperature range of 18-20 °C. In the cooling mode, water temperatures in the ceiling panels were controlled very carefully to avoid the risk of condensation. This was achieved by an automatically controlled rise of the medium cooling temperature if the sensors detected a certain increase in the air humidity. If a window was opened, the system would stop operating (only in the cooling mode). In the heating mode, the radiant ceiling system was running without interruption, with a night-time temperature (from 5 p.m. until 7 a.m.) reduced by 1K, and a weekend temperature reduced by 2 K. In the cooling mode, the system was running continuously with a temperature increase throughout the day depending on rise of the outdoor temperature (i.e. there is a linear temperature compensation depending on the outdoor temperature). With the relatively small night-time and weekend temperature reductions in the heating mode, the energy consumption was somewhat lower. It was possible to turn down the system completely during nights/weekends and start it the next morning (or Monday morning), but this would not considerably reduce the energy consumption. At the same time, the influence on the thermal comfort at the beginning of the working days/weeks would be significant.

The newly installed mechanical ventilation system was providing fresh, tempered air into the offices through channels and nozzles. In offices 2 and 4, which had a larger volume, two inlets were integrated close to the partition wall, and two outlets close to the window area. In Offices 1 and 3, smaller in volume, one inlet was installed close to the partition wall and one outlet close to the window area. The ventilation air was always pre-treated in the air conditioning unit (with a recuperation rate of 70-80 %) to the set temperature and humidity. The ventilation air volume was regulated on the inlets/outlets of the ventilation system. The air flow (volume) was adjusted according to the number of employees assigned to an individual office (35 m^3/h per person), and was adjusted automatically according to CO_2 level. The temperature for the mechanical ventilation system in the heating and cooling seasons was set to 23-24 °C. In the first half of 2013 (when the system started), the mechanical ventilation system operated during working hours only. After some complaints by occupants about the air quality, the system was set to run continuously, i.e. during the night as well.

The energy efficient lighting was achieved via fluorescent dimming lamps. Manual switches were installed to switch the lights on, and to set the desired illuminance level. Each room was equipped with a sensor-controlled switch-off system. The HVAC system and room automation were managed by the building management system (BMS). Its purpose was to collect measured values and give commands to each part of the system according to the measured values and built-in logic. BMS was also designed to enable data exchange between the data acquisition system, control system, automation stations, and the room automation elements.

3. Analysis of measurement results

3.1. Time oscillations of indoor air temperatures

The system was regulated by room regulators placed on the inner office walls, which measured indoor air temperatures. Additionally, indoor air temperatures were measured in each office at five levels vertically over the entire height of the rooms with 5 type T Thermocouple sensors. Verticals with sensors were situated at different locations in individual rooms, but always at least half a metre from the walls, i.e. at approximately 0.25 m (V1), 0.80 m (V2), 1.20 m (V3), 1.80 m (V4) and 2.20 m (V5) from the floor (Figure 2). Air temperature measurements were performed at different heights of the offices in order to assess the air temperature distribution in the cooling and heating modes (including both, the panels and mechanical ventilation). The range of air temperature oscillations and the radiant indoor temperature asymmetry received considerable attention.

The mean indoor air temperatures, calculated from measured values obtained on verticals for representative heating and cooling working weeks, showed a very good performance of the system despite rigorous winter or summer temperature

Table 3. Maximum temperature oscillations of mean indoor air temperature calculated at sensors (V1-V5) at 5 levels

Oscillations temperature in individual offices during heating and cooling		Office 1	Office 2	Office 3	Office 4
11th - 16th February	Daily max temperature oscillation [K]	2.5	2.7	2.1	2.2
	Daily max temperature difference during working hours [K]	1.1	1.4	0.7	0.7
29th July - 3rd August	Daily max temperature oscillation [K]	2.3	2.1	1.4	2.0
	Daily max temperature difference during working hours [K]	1.7	1.4	0.9	1.7

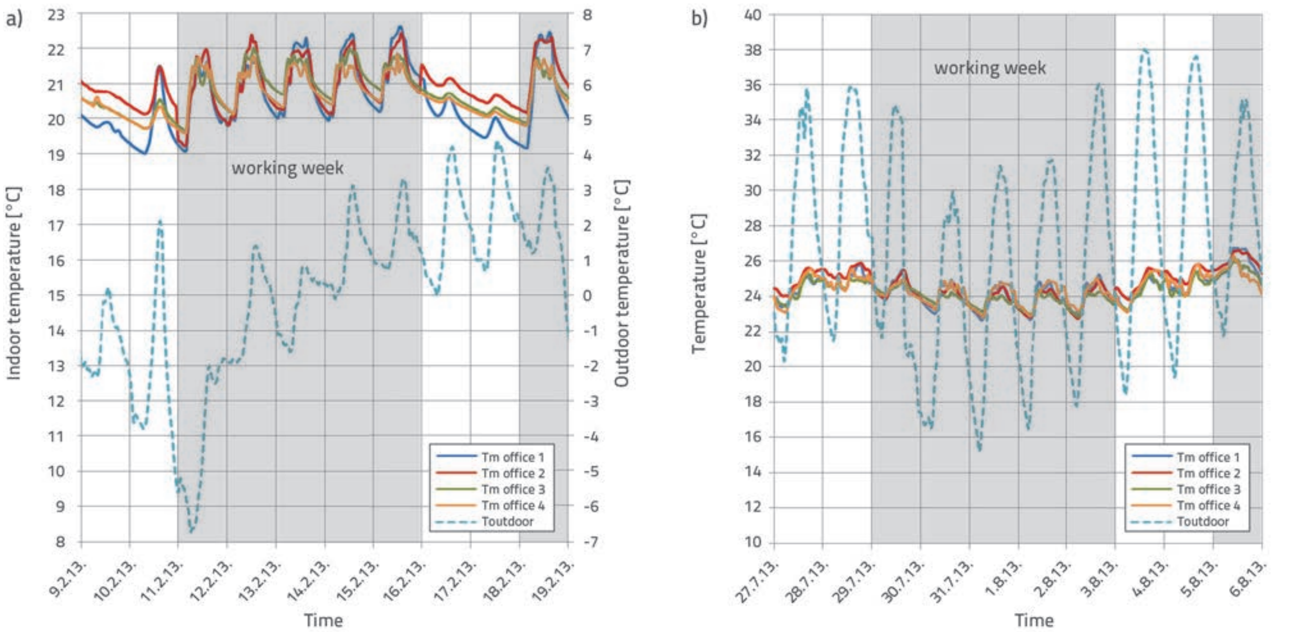

Figure 3. Mean hourly temperatures, T_m, of verticals (V1-V5) in relation to outdoor temperature measured for a) 10 days in winter; b) 10 days in summer

conditions. There were no major daily temperature oscillations of mean indoor air temperatures in any of the four offices (Figure 3).

Mean daily air temperature oscillations between the highest and the lowest values were minimal. Table 3 shows the maximum calculated mean daily air temperature oscillations in individual offices for representative heating and cooling weeks.

3.2. Vertical indoor air temperature differences

Measured temperature differences in the room cross-section varied according to the entire HVAC system operating times. The time-dependent temperature differences in the Office No. 4 for a typical heating working week in February 2013 (Figure 4.a), and for a typical cooling working week in July/August 2013 (Figure 4.b), are shown in Figure 4.

In the typical heating working week, the maximum measured vertical air temperature difference between the highest and the lowest temperature sensors, which occurred in the middle of the working day (at 12 a.m.) was 1.3 K in the Office No. 2; the maximum measured vertical air temperature difference in a typical cooling working week was 0.6K in the Office No. 1. On an average, the temperature difference values never exceeded 0.8 K (heating period) and 0.3 K (cooling period) in the studied offices (Table 4).

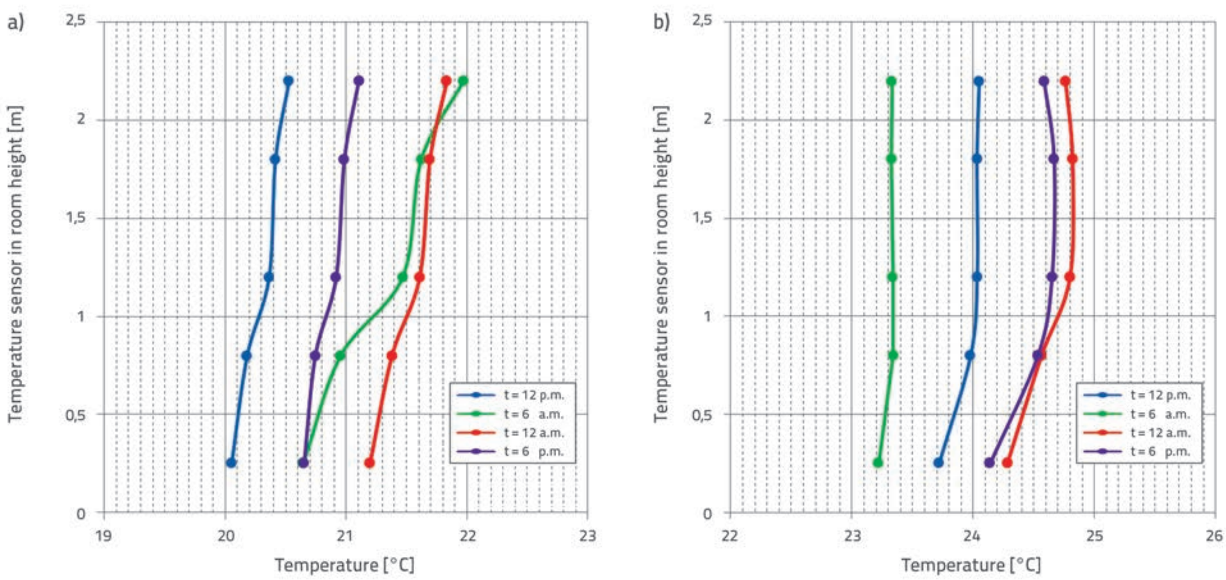

Figure 4. Indoor air temperatures in cross-section of Office 4 at 6 a.m., 12 a.m., 6 p.m., and 12 p.m. for a: a) typical heating working week; b) typical cooling working week

Table 4. Indoor air temperatures measured with temperature sensors (V1-V5) at 5 room levels at noon (12 a.m.)

The internal temperature		Heating period: 11th - 16th February				Cooling period: 29th July - 3rd August			
		Office 1	Office 2	Office 3	Office 4	Office 1	Office 2	Office 3	Office 4
Temperature T [°C] at:	V5 = 2.20 m	21.33	21.07	21.38	21.20	24.24	24.27	24.09	24.28
	V4 = 1.80 m	21.96	22.06	21.64	21.38	24.52	24.41	24.13	24.56
	V3 = 1.20 m	22.02	22.36	21.69	21.61	24.58	24.39	24.14	24.80
	V2 = 0.80 m	22.16	22.35	21.74	21.70	24.78	24.31	24.12	24.82
	V1 = 0.25 m	22.10	22.38	21.77	21.84	24.83	24.39	24.11	24.76
Temperature difference, max [K]		**0.84**	**1.31**	**0.39**	**0.64**	**0.59**	**0.14**	**0.05**	**0.54**
Temperature difference, average [K]		**0.79**				**0.33**			

The measured air temperature difference between V1 (0.25 m) and V3 (1.20 m) above the floor of the offices was less than 0.5 K in the cooling mode, and less than 1.3 K in the heating mode. According to SIST EN ISO 7730, the recommended value for the local thermal comfort level of the vertical air temperature difference, measured 0.1 m and 1.0 m above the floor level (sitting person), in the highest category, Category A, amounts to < 2 K [19].

3.3. Radiant indoor temperature asymmetry

Radiant temperature asymmetry in rooms can cause discomfort to room occupants. It is known that people are more sensitive to radiant asymmetry caused by warm ceiling than they are by cold ceiling [19]. Furthermore, temperature differences between the set temperatures and panel temperatures were much higher in heating conditions compared to cooling conditions. The influence of panels operating in heating mode was therefore assessed in the course of this study.

Maximum indoor air temperature differences between the highest and the lowest temperature sensors, measured during the day in a typical heating working week, were observed early in the morning, around 6 a.m. (Figure 5) when the heating system started to operate. After 8 a.m., the system was rarely activated and the indoor air temperature differences were increasingly reduced, and thus quite uniform indoor air temperatures were registered.

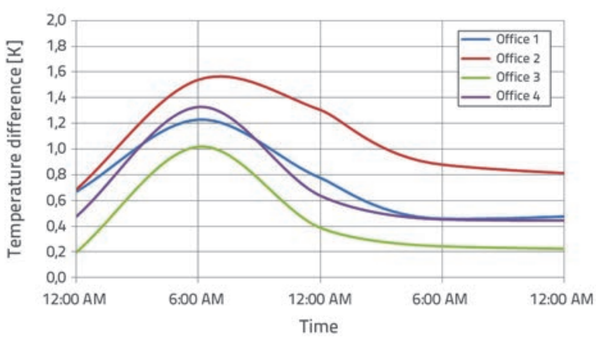

Figure 5. Indoor air temperature differences between highest (V5) and lowest (V1) temperature sensors measured during the day in a typical heating week

The ceiling temperatures, with ceiling panels activated (heating mode), were recorded with the professional IR camera Flir SC640. Thermographic images showed the expected temperature range of the heated panel surface and the concrete slab (Figure 6). The temperature analysis was performed for the worst-case scenario: panels operating at full heating power (in the morning) and with the highest inlet water temperature (38.6 °C). The average temperature, based on measured surface temperatures recorded with the IR camera, which included the entire ceiling surface (60 % panels, 40 % concrete slab), amounted to 27.7 °C. The floor temperature measurements revealed floor temperatures of 22 °C, which resulted in a warm ceiling radiant temperature asymmetry of less than 7K, thus corresponding to Category C according to SIST EN ISO 7730 [19].

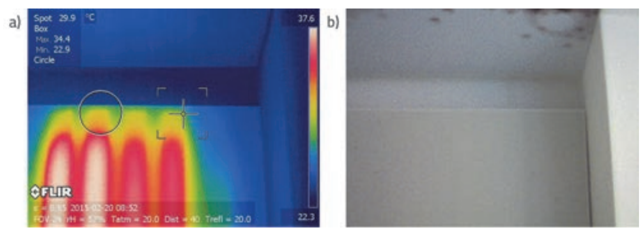

Figure 6. a) screenshot of thermographic recording of activated ceiling panels in heating mode; b) photo of the same section

3.4. Operational performance of ceiling panels

The thermal response of the ceiling panels managing system and of the panels themselves was very good. The panels reacted well to air temperature oscillations and provided the necessary heat or cold (according to heating/cooling mode) to the rooms. The impacts on indoor air temperatures can, for instance, occur due to the occupants opening the windows, additional internal gains caused by devices, or due to solar gains, etc. An example of the relationship between the measured indoor air temperature (blue line), pre-set cooling temperature (violet line), and cooling capacity of panels (green line) is shown in Figure 7. By opening the window in the morning, the occupants could increase the air exchange rate between indoor and outdoor air and consequently lower the indoor air temperature. Two typical situations can be seen in Figure 7: on 23rd April, the indoor air temperature was low enough (below the set temperature), and consequently the panels did not need to cool; on 24th April, the windows were not opened and the indoor air temperature exceeded the temperature set for cooling and, hence, the system started to cool.

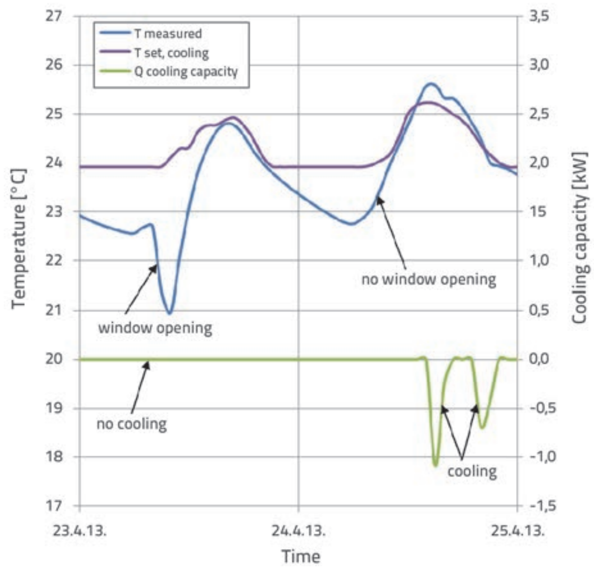

Figure 7. Thermal response of ceiling panel system to indoor air temperature oscillations due to window opening observed over two days during cooling season

3.5. Heating and cooling energy consumption at pilot offices

The heating/cooling ceiling panels of each office were equipped with calorimeters measuring the amount of energy delivered for the heating or cooling of a particular office. The supporting mechanical ventilation system was designed to provide tempered air and thereby a part of the energy to the offices. The mechanical ventilation system inlets and outlets, provided in each room, were therefore equipped with electronic volume regulators and temperature sensors measuring the air temperature and air volume delivered to and extracted from the rooms.

In 2013, the total energy consumption for heating and cooling all four offices amounted to less than 4900 kWh/a. The consumed energy, calculated per area unit of the analysed office area, was 24 kWh/m^2 for heating, and 21 kWh/m^2 for cooling. The monthly consumption of energy for tempering the offices in 2013 is presented in Figure 8.

As the offices were not identical, differing primarily in their equipment and occupancy, the investigation continued by assessing the consumption of heating and cooling energy in individual offices (Figure 9). This assessment was conducted considering the internal gains, which were based on the evaluation of recorded presence of employees, their estimated time of presence in the rooms, and their mainly sedentary activities [19], as well as on the electricity consumption measurements (see Table 5).

Table 5. Internal gains per area unit of pilot offices in 2013

Observed periods	**Internal gains** [kWh/m^2]			
	Office1	Office 2	Office 3	Office 4
Heating period	20.5	33.5	16.9	18.8
Cooling period	13.2	22.0	10.5	11.5

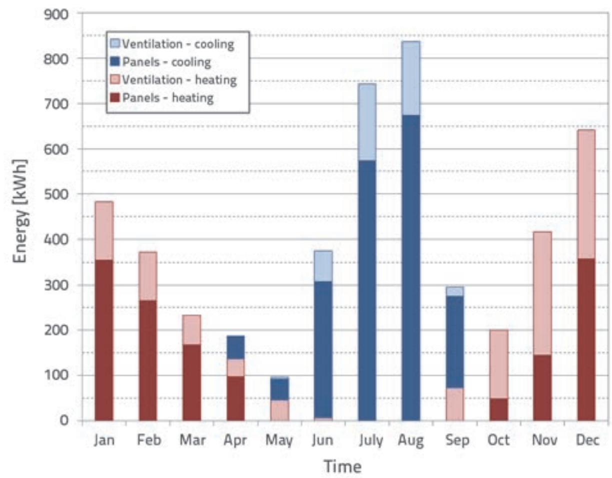

Figure 8. Heating and cooling energy released to pilot offices in 2013

As shown in Figure 9, the highest cooling energy consumption was observed in the Office No. 2, which correspondingly had the highest internal energy gains. The office No. 4 had almost the same floor area as the Office No. 2, but there the internal gains were much smaller so that, with its smaller windows (Table 1), it had the lowest cooling energy consumption per square metre. The highest heating energy consumption per area unit observed in the Office No. 1 can be explained by the fact that it had relatively large window openings per floor area, and a corner that was exposed to the outdoor conditions (Figure 1).

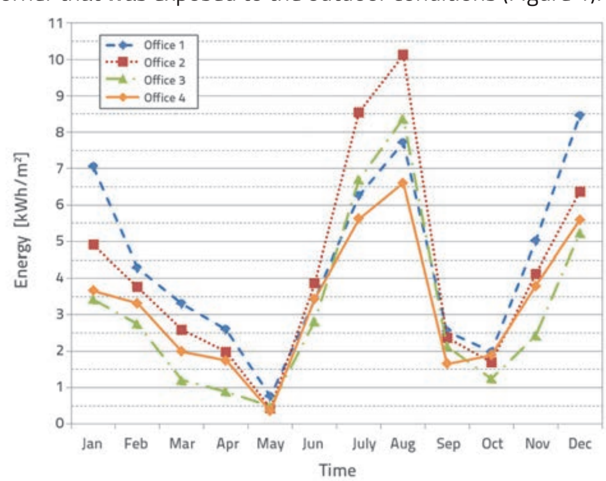

Figure 9. Monthly presentation of heating and cooling energy consumption in 2013 per area unit of individual offices

Calculations of heating energy losses based on TRY (Test Reference Year) for Ljubljana were made at the time when retrofitting of the offices was initially planned. Once all planned measures and data have been included, the calculated energy losses were almost 60 kWh/m^{2}a (71 % transmission, 29 % ventilation losses), while the energy gains were calculated as 35 kWh/m^{2}a (35 % solar, 65 % internal gains). The total heating energy consumption after the retrofit was therefore estimated at 25 kWh/m^{2}a.

The energy consumption before the retrofit was not measured. It was calculated for the heating period only. There was natural ventilation in the offices and the airtightness level was poor. The measured air exchange rate between the indoor and outdoor areas was 13 h^{-1} at the pressure difference of 50 Pa. As a consequence, the ventilation heat losses were huge. Considering this, the calculated results for heating energy consumption of the old offices amounted to approximately 143 kWh/m^{2}a.

4. Conclusions

The analysis and comprehensive study of one-year measurements in the retrofitted pilot offices equipped with radiant ceiling panels providing heat and cold to the rooms was conducted. The complete operation of the system was monitored, and subsequently evaluated. Indoor air temperatures, as related to energy released by the ceiling panel system, supported by the ventilation system, were studied.

The efficiency of the radiant heating/cooling ceiling panels (supported by ventilation), installed in the scope of the retrofitting concept adopted for the offices, was confirmed by the analysis results. The daily indoor air temperature oscillations in the rooms, as well as the maximum vertical temperature differences in both the cooling and heating modes, were within the highest comfort range.

The maximum working day air temperature oscillations were 1.4 K in the heating season and 1.7 K in the cooling season. The highest measured vertical temperature difference, measured at noon, was 1.3 K in the typical heating week, whereas the highest measured vertical air temperature difference in the cooling week was 0.6K. The results of the air temperature differences in the pilot offices equipped with ceiling panels confirmed that the highest category results have been achieved in meeting local thermal criteria for vertical air temperature difference (Category A), both for cooling and heating [19].

The heated ceiling temperatures were observed and analysed since people are highly sensitive to radiant asymmetry caused by e.g. warm ceiling. Measurement results showed that in this case study the warm ceiling radiant temperature asymmetry was less than 7 K. This study also confirmed that the large surface low-temperature heating principle adopted in pilot offices provided thermally comfortable indoor environment, even though the heat source was located above the head level. The results confirmed compliance with local thermal criteria not only for cooling but also for heating: it may be expected that the radiant temperature asymmetry corresponds to Category C, or better [19].

It was established that the activity of occupants and some events can also influence operation of the ceiling panels. On the other hand, the measured values indicated that the radiant ceiling heating/cooling system was fully able to respond quickly and effectively cope with temperature oscillations. Nevertheless, the frequency, intensity and duration of these events are important. Further research is needed to define with a higher accuracy which impacts can be compensated, and where the limits of the system are.

Considering the restrictions of the retrofitting measures, the energy needs for tempering the pilot offices were at a very satisfactory level. With 24 kWh/m^{2}a of energy consumption for heating, and 21 kWh/m^{2}a for cooling, the retrofitted pilot offices can be defined as very low-energy offices. Since large ceiling-mounted radiant surfaces use the principle of small temperature differences for heating and cooling, the energy for tempering the indoor environment can be provided quite efficiently.

Based on experimental and measuring methods, this study proves that the radiant ceiling panels in the retrofitting concept used are operating well in Ljubljana weather conditions. Combined with a ventilation system and good solar protection, they provide a highly satisfactory thermal comfort. The comprehensive analyses carried out in the scope of this experimental study confirm adequacy of the use of the radiant ceiling panels for both cooling and heating. On the one hand, the study partly justifies generalization of the above presented technical concept while underlying, on the other hand, the necessity for further verifications in a wider spectrum of weather conditions.

Acknowledgements

The authors would like to thank the European Commission for financial support provided through the EU project *Resource- and Cost-Effective Integration of Renewables in Existing High-Rise Buildings*, 7FP, 2008-2012, which contributed to the realisation of the pilot demonstration at ZAG.

REFERENCES

[1] Europe's Buildings Under the Microscope: a country-by-country review of the energy performance of buildings, The Buildings Performance Institute Europe, BPIE, Brussels, BPIE, October 2011, http://www.institutebe.com/InstituteBE/media/Library/Resources/Existing%20Building%20Retrofits/Europes-Buildings-Under-the-Microscope-BPIE.pdf, 10.12.2014.

[2] EPBD Recast: Directive 2010/31/EU of the European Parliament and of the Council of 19 May 2010 on the Energy Performance of Buildings (recast), http://www.eceee.org/policy-areas/buildings/EPBD_Recast/EPBD_recast_19May2010.pdf, 15.12.2014.

[3] Bonacci, O.: Analysis of mean annual air temperature series in Croatia, *Građevinar*, 62 (2010) 9, pp. 781-791.

[4] Andres-Chicote, M., Tejero-Gonzales, A., Velasco-Gomez, E., Rey-Martinez, F.: Experimental study on the cooling capacity of a radiant cooled ceiling system, *Energy and Buildings,* 54 (2012), pp. 207-214, http://dx.doi.org/10.1016/j.enbuild.2012.07.043

[5] Causone, F., Corgnati, S. P., Filippi, M., Olesen, B. W.: Solar radiation and cooling load calculation for radiant systems definition and evaluation of direct solar load, *Energy and Buildings*, 42 (2010), pp. 305-314, http://dx.doi.org/10.1016/j.enbuild.2009.09.008

[6] Jeong, J. W., Mumma, S. A.: Practical cooling capacity estimation model for a suspended metal ceiling radiant panel, *Building and Environment*, 42 (2007), pp. 3176-3185, http://dx.doi.org/10.1016/j.buildenv.2006.08.006

[7] Fonseca-Diaz, N., Lebrun, J., Philippe, A.: Experimental study and modelling of cooling ceiling systems using steady-state analysis, *International Journal of Refrigeration*, 33 (2010) 4, pp. 793-805, http://dx.doi.org/10.1016/j.ijrefrig.2009.12.011

[8] Rees, S. J., Haves, P.: An experimental study of air flow and temperature distribution in a room with displacement ventilation and chilled ceiling, *Building and Environment*, 59 (2013) 1, pp. 358-368, http://dx.doi.org/10.1016/j.buildenv.2012.09.001

[9] Venko, S., Vidal de Ventos, D., Arkar, C., Medved, S.: An experimental study of natural and mixed convection over cooled vertical room wall, *Energy and Buildings,* 68 (2014) 1, pp. 387-395, http://dx.doi.org/10.1016/j.enbuild.2013.09.014

[10] Rahimi, M., Sabernaeemi, A.: Experimental study of radiation and free convection in an enclosure with a radiant ceiling heating system, *Energy and Buildings,* 42 (2010) 11, pp. 2077-2082, http://dx.doi.org/10.1016/j.enbuild.2010.06.017

[11] Fonseca, N.: Experimental analysis and modeling of hydronic radiant ceiling panels using transient-state analysis, *International Journal of Refrigeration,* 34 (2011) 4, pp. 958-967, http://dx.doi.org/10.1016/j.ijrefrig.2011.01.007

[12] Fonseca, N., Cuevas, C., Lemort, V.: Radiant ceiling systems coupled to its environment part 1: Experimental analysis, *Applied Thermal Engineering,* 30 (2010), pp. 2187-2195, http://dx.doi.org/10.1016/j.applthermaleng.2010.05.033

[13] Imanari, T., Omori, T., Bogaki, K.: Thermal comfort and energy consumption of the radiant ceiling panel system. Comparison with the conventional all-air system, *Energy and Buildings,* 30 (1999), pp. 167-175, http://dx.doi.org/10.1016/S0378-7788(98)00084-X

[14] Miriel, J., Serres, L., Trombe, A.: Radiant ceiling panel heating-cooling systems: experimental and simulated study of the performances, thermal comfort and energy consumption, *Applied Thermal Engineering,* 22 (2002), pp. 1861-1873, http://dx.doi.org/10.1016/S1359-4311(02)00087-X

[15] Fonseca-Diaz, N.: Modelling of a hydronic ceiling system and its environment as energetic auditing tool, *Applied Energy,* 88 (2011), pp. 636-649, http://dx.doi.org/10.1016/j.apenergy.2010.08.005

[16] SIST EN 13829 Thermal performance of buildings - Determination of air permeability of buildings - Fan pressurization method, SIST, 2001.

[17] Technical Guideline: TSG-1-004 Efficient use of energy, Ministry of the Environment and Spatial Planning, 2010, http://www.arhiv.mop.gov.si/fileadmin/mop.gov.si/pageuploads/zakonodaja/prostor/graditev/TSG-01-004_2010.pdf, 03.08.2010.

[18] Rules on efficient use of energy in buildings PURES 2010, Official Journal of the Republic of Slovenia, 2010. http://www.pisrs.si/Pis.web/pregledPredpisa?id=PRAV10043, 04.02.2015.

[19] SIST EN ISO 7730, Ergonomics of the thermal environment - Analytical determination and interpretation of thermal comfort using calculation of the PMV and PPD indices and local thermal comfort criteria, European standard, CEN, 2006.