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Dissertation Thesis Abstract

Low temperature heating and high temperature cooling with innovative materials

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STU

Abstract

This dissertation thesis explores the efficiency and effectiveness of radiant heating and cooling systems in office buildings, aiming to provide sustainable and energy-efficient solutions. Phase change materials (PCMs) are currently being explored for their advantageous properties in building heating and cooling applications. This innovative material demonstrates potential use in renovations, where its similar properties to TABS can be leveraged. The heat flux calculations presented in the dissertation showed closer results using the computational model ISO 11855-2 for TABS systems. Five case studies from Denmark, Canada, Germany, the Czech Republic, and Latvia were used to determine the calculated heat fluxes, which were compared with measured results. Indoor thermal environment in buildings has been studied for many years, highlighting the importance of thermal comfort and the continuous development of technologies to enhance indoor environments. An innovative material, foamed aluminium, currently under research, was assessed for thermal comfort for employees in an open office. The results show high thermal conductivity of the material and a rapid response of the system. Foamed aluminium radiant ceiling panels provide optimal thermal comfort for year-round operation, although deficiencies were observed in terms of assessing relative air humidity during the winter months. Thermally active building systems are increasingly being utilized as a suitable combination of heating and cooling systems using renewable energy sources. In the final objective, we focused on energy evaluation of an office building equipped with two ground-source heat pumps. Geothermal wells serve as the renewable energy source. This year-round operation ensures optimal thermal comfort for both summer and winter months, with the heat pumps turned off during the summer period, and cooling achieved through passive operation.

Keywords:

radiant heating, radiant cooling, phase change materials, thermally activated building systems, ceiling panels, energy efficiency, geothermal heat pumps

Abstrakt

Táto dizertačná práca skúma účinnosť a efektivitu sálavých systémov na vykurovanie a chladenie v kancelárskych budovách s cieľom poskytnúť udržateľné a energeticky efektívne riešenia. Fázová premena materiálov (PCM) je v súčasnosti zameraná na využitie ich výhodných vlastností v oblasti vykurovania a chladenia v budovách. Tento materiál preukazuje vhodné využitie pri rekonštrukciách, kde je možné využiť ich totožné vlastnosti s TABS. Výpočet tepelného toku, ktorý bol uvedený v dizertačnej práci naznačuje, že bližšie výsledky sú prostredníctvom výpočtového modelu ISO 11855-2 pre TABS systémy. Päť prípadových štúdií z Dánska, Kanady, Nemecka, Českej republiky a Lotyšska bolo zvolených pre vypočítanie tepelného toku. Vypočítané výsledky boli následne porovnávané s nameranými výsledkami. Vnútorné prostredie v budovách je skúmané mnoho rokov. Toto preukazuje dôležitosť tepelného komfortu v interiéroch a tým aj neustále vyvíjanie technológií na skvalitnenie vnútorného prostredia. Inovatívny materiál- napenený hliník, ktorý je v súčasnosti predmetom výskumu bol posudzovaný z hľadiska tepelnej pohody pre zamestnancov vo veľkopriestorovej kancelárii. Výsledky ukazujú vysokú tepelnú vodivosť materiálu a s tým aj spätú rýchlu odozvu systému. Stropné panely z napeneného hliníka zabezpečujú optimálne tepelné prostredie pre celoročnú prevádzku. Nedostatočné hodnoty sa ukázali z hľadiska posúdenia na relatívnu vlhkosť vzduchu počas zimného obdobia. Tepelne aktivované stavebné systémy sa využívajú v súčasnosti čoraz častejšie, preukazujú sa ako vhodná kombinácia systému vykurovania a chladenia s využitím obnoviteľného zdroja energie. V poslednom cieli sme sa zamerali na energetické vyhodnotenie prevádzky pre administratívnu budovu, ktorá má dve tepelné čerpadlá zem voda. Zdrojom obnoviteľnej energie sú geotermálne vrty. Táto celoročná prevádzka zabezpečuje optimálne tepelné prostredie aj pre letné a zimné mesiace, pričom počas letného obdobia sú tepelné čerpadlá vypnuté a chladenie je realizované cez pasívne chladenie.

Kľúčové slová:
sálavé vykurovanie, sálavé chladenie, fázová zmena materiálu, tepelne aktivované stavebné systémy, stropné panely, energetická účinnosť, tepelné čerpadlá

1. INTRODUCTION

Low temperature heating and high temperature cooling can provide efficient and sustainable building technical equipment, ensuring optimal conditions for both residential and working indoor environments in buildings. This development is a result of the increased demand for energy-efficient solutions in an effort to reduce energy consumption for heating and cooling, as well as to decrease greenhouse gas emissions. Low temperature heating utilizes lower supply temperatures for space heating (compared to other types of heating, such as convection heating), which allows achieving thermal comfort with less energy demand, thereby reducing energy consumption. On the other hand, high temperature cooling focuses on removing accumulated heat from interiors, where radiant systems with supply temperatures of the heat-carrying medium above 16 °C are used, enabling effective cooling of buildings during warm periods of the year. The advantage of these radiant heating and cooling methods is the possibility of using renewable energy sources (such as heat pumps), which ensure year-round operation. Radiant panels with phase change materials used for cooling, represents a modern and energy-efficient method of maintaining a comfortable indoor temperature in buildings during summer. The suitability of this modern cooling method is particularly emphasized during renovations, as these radiant panels possess very similar properties to thermally active building systems (TABS). Thermally active building systems (TABS) are a construction method of radiant heating and cooling, where heat-carrying pipes are embedded into the structural components. This method is limiting and is therefore suitable for newly constructed buildings where the design phase occurs before the construction of the main structure. TABS utilize the high thermal capacity of building materials, such as concrete or plaster, to store and exchange heat or cold between the structure and the building's internal environment. The aims of dissertation thesis are to explore and analyse the issues related to low temperature heating and high temperature cooling in administrative buildings. The dissertation thesis not only addresses on the technical aspects of these systems but also their environmental and social impacts. Based on this analysis and evaluation, it will be possible to use these researched results to develop optimal solutions for future projects in the field of building heating and cooling.

2. STATE OF THE ART

The fundamental legislation relating to the general guidelines for the energy performance of buildings **European Parliament and Council Directive 2010/31/EU**. Describes the basic characteristics of heating systems and their effective use, taking into account the economy of buildings. Calculated or measured quantity of energy needed should satisfy the demand for the common use of the building that includes energy used for heating, cooling, ventilation, hot water and lighting. Another directive that affects the design of radiant systems is **a Directive 2018/2001 of the European Parliament and of the Council on support for renewable energy**. Using a combination of heating and cooling in the building, the source producing heat and cold, which we can use is the only source the heat pump. Directive 2018/2001 on the promotion of renewable energy describes the use of energy from renewable energy and within the Paris agreement, says climate and energy sources, where, by 2030 aims to reduce emissions by 40% compared to 1990. Another objective is to ensure development of heating and cooling measures in buildings, using renewable sources. **Law no. 355/2007 Coll. the act on protection, promoting and development of public health and the amendment of certain acts** speaks of the overall health of people for specific operations and also general risk conditions for persons and subsequent health protection recommendations. According to this law, the internal environment of buildings, which must meet the requirements for thermal and humidity microclimate, ventilation and heating, lighting requirements and other types of radiation. **Decree no. 259/2008, Decree no. 210/2016, Decree no. 99/2016** describes the hygro-thermal microclimate in the space, and talks about optimal and permissible values for thermal and humidity microclimate for both hot and cold period of the year and also about health care prior to load and cold at work. Technical standards are divided into two groups, the first group concerns the internal environment of buildings and thermal moisture microclimates and the second group of technical standards indicates specific standards for designing and the basic distribution of radiant systems, where the design, division and assembly of radiant systems. All these legislative regulations and technical standards indicate a comprehensive explanation and the quality of the correct design of radiant systems and the overall security of the internal space that will be healthy for living and working space.

Principle of radiant systems

Factors affecting the heating and cooling capacity of radiant systems include the heat exchange coefficient between the radiant surface and the internal space (total heat exchange coefficient = convection + radiation), the surface temperatures adjusted for the thermal comfort of the occupants, the dew point in the space, the heat transfer between the tubes and the surface, the emissivity of the radiant surface, and the view angle between the tubes and the angular factors between the space and its surfaces. On *Fig. 2.5* is depicted the transmission of heat through the ceiling, the floor, through window structures and heat through the shoe.

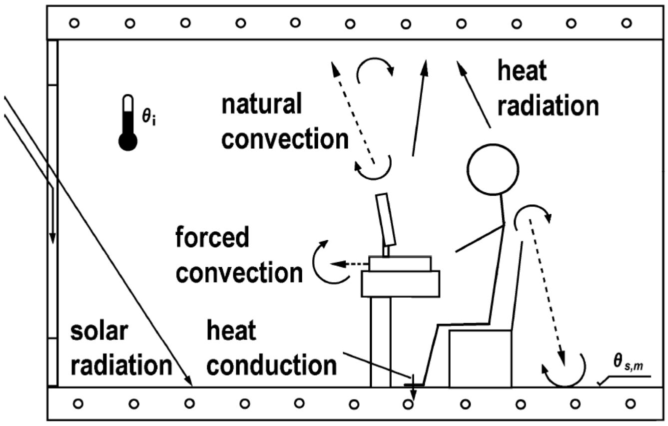


Fig. 2.5 Thermal balance model of a room

3. AIMS OF THE RESEARCH

The general aim of the dissertation thesis is to explore radiant systems for heating and cooling in more detail and to contribute new information that will be useful for practice and society. The planned contributions of the dissertation thesis include providing examples of various practical applications of radiant systems in office buildings and their potential for application in other types of buildings. The focus will also be on future trends and innovative solutions in the field of radiant systems, as well as the potential for their further development and application in the future.

3.1 Design calculations of heat flux for radiant ceiling panels with phase change materials (PCMs)

In the first objective, we focused on the computational model for radiant ceiling panels with phase change material (PCM). To establish the computational model, it is essential to calculate the resulting heat fluxes. Five radiant ceiling panels from Denmark, Canada, Germany, the Czech Republic, and Latvia were selected based on the specified required characteristics so that the calculations had approximately the same input data, allowing us to subsequently compare the results. Phase change materials (PCM) are an innovative materials without an established computational model, our goal was to assess the calculated heat flux on the surface of ceiling panels designated for cooling during the summer period and subsequently compare these with actual measured values. The computational procedure for the radiant ceiling panels was conducted using two methodologies: ISO 11855-2 (standard describing the computational model for Thermally Active Building Systems, TABS) and ISO 18566-3 (standard describing the computational model for radiant ceiling panels). The calculated heat fluxes were subsequently assessed and compared with the measured data. The input data for the calculations were considered under the same conditions as those set during the measurements. The calculations were processed for daily evaluations during the summer period when the radiant panels were in passive mode, meaning the water circulation system for cooling was turned off.

3.2 Evaluation of indoor thermal environment with the radiant heating and cooling system through a foamed aluminium radiant ceiling panels

In the second objective, we focused on assessing the indoor environment of an open office, where innovative ceiling radiant panels made from foamed aluminium were used for year-round operation. Tubes were embedded into these panels, and heated or cooled heat transfer fluid was circulated through them, used for heating or cooling the space. This conductive material is capable of responding very quickly to heat and cold sources. We assessed the operation of an open office to determine the overall performance of heating and cooling systems and their impact on indoor environmental parameters. We evaluated the indoor temperatures at multiple measured points within the office and the relative humidity levels throughout the space. Additionally, we examined the supply and return temperatures of the heat transfer fluid circulating within the office. The primary goal was to assess the performance of heating and cooling during the years when the air conditioning unit was installed in the office, which was used solely for air exchange, and the years when air conditioning unit was not installed. We also focused on evaluating weekend operations when the open office was unoccupied, and the airconditioning unit had not yet been installed. All assessments were conducted separately for the winter and summer periods of the examined years.

3.3 Energy evaluation of thermally active building systems in office building

In the final objective, we focused on the energy evaluation of an office building equipped with a heating and cooling system utilizing thermally active building systems (TABS). Pipes embedded in the structural concrete provided heating and cooling to the entire ceiling structure. Since this type of system also qualifies as a radiant heating and cooling system, we aimed to evaluate the generated heat and cold as well as the consumed electrical energy used for heating and cooling. The source of heat and cold was renewable energy from two ground-source heat pumps. The energy harnessed from geothermal boreholes was used year-round for heating and cooling the office building. The outcome will be an energy assessment that evaluates the produced heat and cold from the heat pumps and the consumed electrical energy, divided into summer and winter operations.

4. DESIGN CALCULATIONS OF HEAT FLUX FOR RADIANT CEILING PANELS WITH PHASE CHANGE MATERIALS (PCMs)

This study aimed to compare the heat flux calculation for 5 radiant panels with PCM according to ISO 11855-2 for TABS, ISO 18566-3 for the radiant panels and empirical calculation according to the Rehva guidebook. All radiant panels have a water pipe system, incorporating phase change material in the ceiling panel structure and all ceiling panels were evaluated for cooling operation. Found ceiling panels incorporating the PCM are from Denmark, Canada, Germany, Czech Republic and Latvia. All input data collected from published research can be found in *Tab. 4.1*. These input data were utilized for heat flux calculation for ISO 11855-2 for TABS and ISO 18566-3 for the radiant panels.

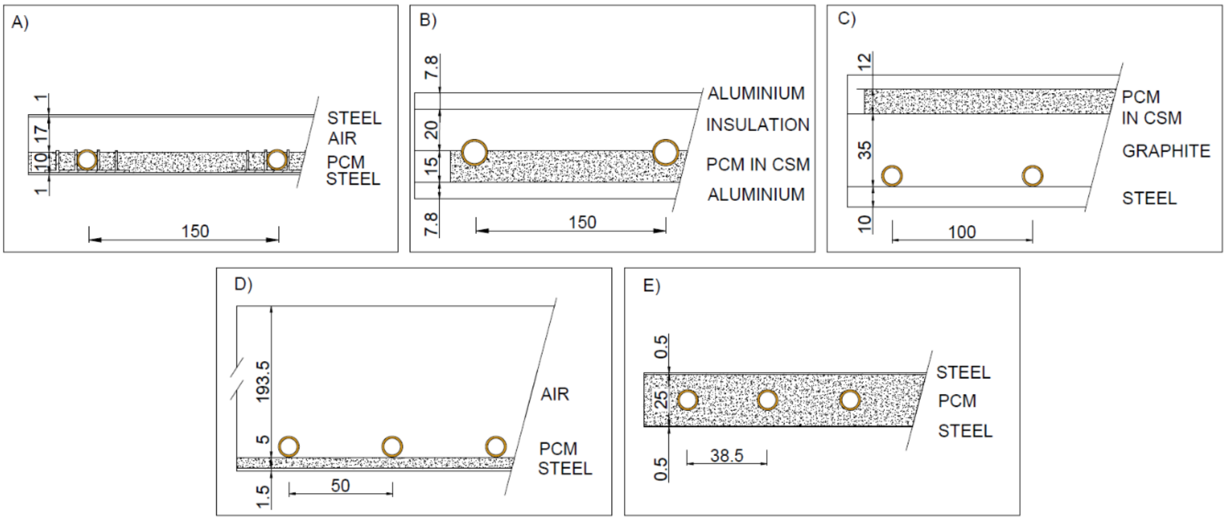


Fig. 4.1 Cross-section of ceiling panels with PCM, A) Denmark, B) Canada, C) Germany, D) Czech Republic, E) Latvia (values are given in millimetres and the cross-section is not to scale)

Tab. 4.1 Overview of input data about radiant panels with PCM from the evaluated literature

	ARTICLE				
	DENMARK	*CANADA*	*GERMANY*	*CZECH REP.*	*LATVIA*
Area of the radiant panel (m^2)	0.354	0.720	0.391	0.960	0.500
Pipe spacing (m)	0.15	0.15	0.10	0.05	0.0385
Pipe diameter (m)	0.01	0.0127	0.01	0.01	0.008
The thickness of the pipe wall (m)	0.001	0.001	0.001	0.001	0.0005
Thermal conductivity of pipe ($W.m^{-1}.K^{-1}$)	390	390	390	395	386.6

Thermal conductivity of PCM (W.m^{-1}.K^{-1})	0.20	0.15	0.60	0.18	0.20
Dimension of PCM (m)	0.01	0.015	0.012	0.005	0.025
Thermal conductivity of added material layer (W.m^{-1}.K^{-1})	0.024 (air)	0.04 (insulation)	9.0 (graphite)	0.024 (air)	-
Thickness of added material layer (m)	0.017	0.02	0.035	0.1935	-
Thermal conductivity of radiant panel sheet (W.m^{-1}.K^{-1})	50.00	100.00	15.00	15.00	16.27
Thickness of radiant panel sheet (m)	0.001	0.0078	0.001	0.0015	0.0005
Design return water temperature (°C)	21	18	18	13	18
Supply water temperature (°C)	18	15	16	10	15
Design indoor temperature (°C)	26	26	26	26	26

Calculation method according to TABS

ISO 11855-2 describes the design method for embedded radiant heating and cooling systems. The research from last year shows that PCM in the ceiling panel and TABS have the main characteristic features very equal. The TABS has water pipes embedded into the concrete slab. The calculation method was considered for type system E, with all properties from the radiant ceiling panel with PCM. For TABS types E and F, the design of heat flux is according to the thermal resistance method.

The heat flux at the surface q (W/m^2) utilizes the thermal resistance method:

$$q = K_H . \Delta\theta_H \qquad \text{(W/m}^2\text{)} \qquad (4.1)$$

Where K_H , equivalent heat transmission coefficient for type E is:

$$K_H = \frac{1}{(R_W + R_r + R_X + R_i)} \qquad \text{(W/(m}^2\text{.K))} \qquad (4.2)$$

Cooling medium differential temperature $\Delta\theta_H$ is calculated:

$$\Delta\theta_H = \frac{\theta_R - \theta_V}{ln\frac{\theta_v - \theta_i}{\theta_R - \theta_i}} \qquad \text{(K)} \qquad (4.3)$$

where:

θ_R is the return temperature of the cooling medium (°C),

θ_V supply temperature of cooling medium (°C),
θ_i design indoor temperature (°C).

By the turbulent flow of the medium inside the pipe, the resistance between the fluid and the pipe wall is calculated:

$$R_W = \frac{W^{0.13}}{8.\ \pi} \left(\frac{d_a - 2.\ s_r}{m_{H,sp}.\ l}\right)^{0.87} \qquad ((m^2.K)/W) \qquad (4.4)$$

where:
W is pipe spacing (m),
d_a is pipe wall thickness (m),
s_r is pipe wall thickness (m),
$m_{H,sp}$ is design cool flow rate (kg/s),
l is pipe circuit length (m).

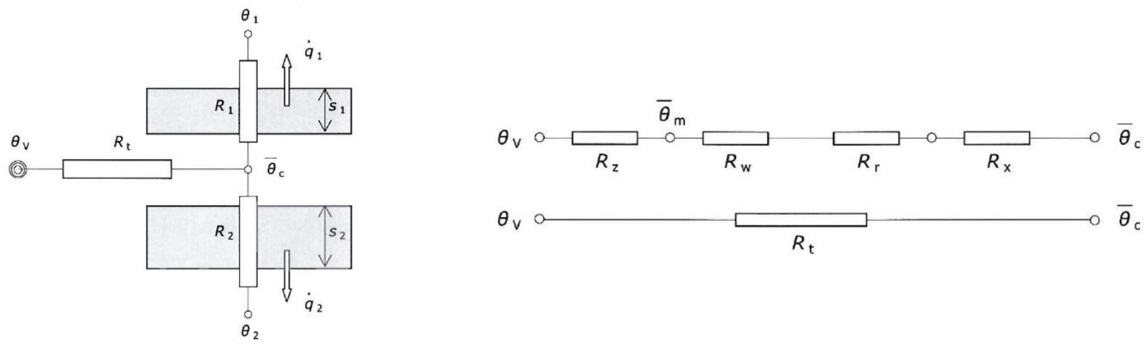


Fig. 4.2 Resistance network (left) and overall resistance network (right)

For calculation of the design cooling flow rate:

$$m = \frac{A_F.q}{\sigma.c_W} \left(1 + \frac{R_0}{R_u} + \frac{\theta_i - \theta_u}{q.R_u}\right) \qquad (kg/s) \qquad (4.5)$$

where:
A_f is an effective area (m^2),
q is heat flux (W/m^2),
σ is temperature drop (K),
c_W is the specific heat capacity of water (J/(kg. K)),
R_0 is the upwards partial heat transmission resistance of the structure ($(m^2.K)/W$),
R_u is the downwards partial heat transmission resistance of the structure ($(m^2.K)/W$),
θ_i is the standard indoor room temperature in accordance with ISO 11855-2 (°C),
θ_u is the indoor temperature of a room under the floor heated room (K).

Concerning the thermal resistances, the following equations are valid:

$$R_o = \frac{1}{h} + R_{\lambda,B} + \frac{s_u}{\lambda_u} \qquad ((m^2.K)/W) \qquad (4.6)$$

where:
1/h is the heat transfer resistance on the heating ceiling surface ((m^2.K)/W),
$R_{\lambda,B}$ is thermal resistance of material in the upper part of construction ((m^2.K)/W),
s_u dimension of material, in which embedded the pipes (m),
λ_u thermal conductivity of the material, in which are embedded the pipes (m/(K.W)) .

$$R_u = R_{\lambda,ins} + R_{\lambda,floor} + R_{\lambda,plaster} + R_{\lambda,floor} \quad ((m^2.K)/W) \qquad (4.7)$$

where:
$R_{\lambda,ins}$ is thermal resistance of material above the pipes, insulation ((m^2.K)/W),
$R_{\lambda,floor}$ is thermal resistance of material above the pipes, floor construction ((m^2.K)/W),
$R_{\lambda,plaster}$ is thermal resistance of material above the pipes, plaster ((m^2.K)/W),
$R_{\lambda,floor}$ is thermal resistance of material above the pipes, floor construction, last material ((m^2.K)/W).

The resistance of the pipe wall is defined through:

$$R_r = \frac{W.\ln\left(\frac{d_a}{d_a - 2.s_r}\right)}{2.\pi.\lambda_r} \quad ((m^2.K)/W) \qquad (4.8)$$

where:
λ_r is the thermal conductivity of the pipe wall (m/(K.W)).

The resistance between the pipe outside wall and the conductive layer can be described:

$$R_x = \frac{W.\ln\left(\frac{W}{\pi.d_a}\right)}{2.\pi.\lambda_b} \quad ((m^2.K)/W) \qquad (4.9)$$

where:
λ_b is the thermal conductivity of a material, where the pipes are embedded (m/(K.W)).

The heat transfer coefficient U_i is calculated according to:

$$U_i = \frac{1}{\left(\frac{1}{h_i} + \frac{s_i}{\lambda_b}\right)} \quad (W/(m^2.K)) \qquad (4.10)$$

where:
h_i is heat transfer coefficient (W/(m^2 .K)),
s_i is the dimension from the centre the of the pipe to the end of the construction (m).

The corresponding resistances are:

$$R_i = \frac{1}{U_i} \quad ((m^2.K)/W) \qquad (4.11)$$

Calculation method according to radiant panel

For the second determination of heat flux between surface and space for radiant panel with PCM was calculated the method according to ISO18566-3 for the radiant panels. This standard describes the design, test method and control for hydronic radiant and cooling panel systems.

Heat flux at the surface q utilizes the resistance method:

$$q = K_H . \Delta\theta_H \qquad (W/m^2) \qquad (4.1)$$

Where K_H , equivalent heat transmission coefficient for radiant panel is:

$$K_H = \frac{1}{(R_u + R_i)} \qquad (W/(m^2.K)) \qquad (4.12)$$

Cooling medium differential temperature $\Delta\theta_H$ is calculated:

$$\Delta\theta_H = \frac{\theta_R - \theta_V}{ln\frac{\theta_v - \theta_i}{\theta_R - \theta_i}} \qquad (K) \qquad (4.3)$$

θ_R is the return temperature of the cooling medium (°C),
θ_V is the supply temperature of the cooling medium (°C),
θ_i is designed for indoor temperature (°C).

Characteristic panel thermal resistance:

$$r_u = r_t . M_p + r_s . M_p + r_p + r_c \qquad ((m^2.K)/W) \qquad (4.13)$$

where:
r_t is the thermal resistance of pipe wall per unit pipe spacing in a hydronic system (m.K)/W),
M_p is pipe spacing (m),
r_s is thermal resistance between the pipe and the panel per unit spacing ((m.K)/W),
r_p is the thermal resistance of panel ((m^2.K)/W),
r_c is the thermal resistance of panel covers ((m^2.K)/W).

The thermal resistance of pipe wall per unit pipe spacing:

$$r_t = \frac{\ln\left({D_0}/{D_i}\right)}{2.\pi.k_t} \qquad ((m.K)/W) \qquad (4.15)$$

where:
d_0 is the outside diameter of pipe (m),
d_i is the inside diameter of pipe (m),
k_t is the thermal conductivity of pipe (W/(m. K).

The heat transfer coefficient U_i is calculated according to:

$$U_i = \frac{1}{\left(\frac{1}{h_i} + \frac{s_i}{\lambda_b}\right)} \qquad (W/(m^2.K)) \qquad (4.16)$$

where:
h_i is heat transfer coefficient (W/(m^2.K)),
s_i is the dimension from the centre of the pipe to the end of the construction (m).

The corresponding resistances are:

$$R_i = \frac{1}{U_i} \qquad ((m^2.K)/W) \qquad (4.17)$$

Radiant cooling panels incorporating PCM were calculated according to the standard for TABS, where the PCM was taken into account. This transformation of calculation for TABS can be considered as correct, because the measure values of heat flux are close. Also the simulation model made by Yasin et al. shows that the heat flux measure and simulation are very similar according to the TABS method of calculation in the simulation model. Radiant panel calculation according to the standard shows that the values of heat flux are quite higher than the average measured value. This calculation considered the thermal resistance of the ceiling panel sheet, the thermal resistance of pipes and the dimension of pipe spacing. This calculation was not contemplated by the PCM.

Tab. 4.2 Results of heat flux between surface and space

Heat flux		DENMARK (W/m^2)	CANADA (W/m^2)	GERMANY (W/m^2)	CZECH. REP. (W/m^2)	LATVIA (W/m^2)
TABS for PCM	**ISO 11855**	15.4	16.8	72.8	29.6	39.5
Radiant Panel with PCM	**ISO 18566**	60.2	66.8	88.7	150.3	61.2
Measured values		5.3 - 27.7	11.0 - 31.4	11.0 - 16.0 *	10.0 - 29.0	-
Average value (measured)		11.3	17.3	-	25.0	-
Day Water Pipe Circulation operation		OFF	OFF	OFF	OFF	OFF

* heat flux measured at the bottom surface layer of PCM

Partial conclusion

Currently, there is no standardized calculation method for determining the design heat flux between the surface and the indoor space in a radiant panel with PCM. In this research, five radiant panel systems with PCM were chosen from existing literature to compare the measured heat flux with the heat flux calculated using established standards for other radiant systems. The heat flux calculated according to ISO 11855-2 closely matched the measured values. However, standards ISO 18566-3 yielded significantly different results, deviating substantially from the reported values in the studied literature, which were on average five times higher. Future studies should concentrate on developing the TABS calculation method for various types of radiant panels incorporating PCM, considering different configurations such as the spacing between water pipes and the sequence of material layers.

5. EVALUATION OF INDOOR THERMAL ENVIRONMENT WITH THE RADIANT HEATING AND COOLING SYSTEM THROUGH A FOAMED ALUMINIUM RADIANT CEILING PANELS

The application of radiant panels, where the subsequent assessment was made is located in the building Hydro profiles a.s, in Žiar nad Hronom. The Institute of Materials and Machine Mechanics, in collaboration with the Slovak Academy of Sciences, conducted research on aluminium material. As a result of their investigation, they developed foamed aluminium, which was then utilized in the production of radiant panels. These panels were subsequently installed in a open office measuring 260 m^2 at Hydro a.s. The open office area is designed for 16 people.

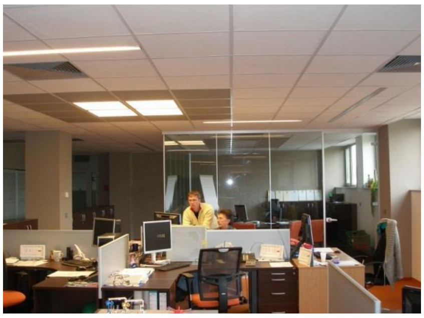


Fig. 5.1 Interior of open office in Žiar nad Hronom

This newly created 600 x 600 mm radiant panel from aluminium foam has a very good thermal conductance of the material, where the change of temperature might be quickly changed in the entire area of the radiant panel, not only the tubes that transport needed heat/cool water. Spacing between the pipes is 300 mm.

Fig. 5.2 The radiant panel with pipes in foam aluminium

Aim of the study

In this chapter, the main objectives of the study for an open office will be focused on heating and cooling performance and assessment the indoor thermal environment. Specifically, the assessment will concentrate on various parameters related to the indoor thermal environment and the evaluation of thermal comfort for individuals working in the office.

1) **Determining the heating and cooling performance of foamed aluminium radiant ceiling panels during air-conditioning operation**

By determining the heating and cooling performances, we can find out the percentage of utilization of the heating and cooling system, determine its efficiency, and assess its potential for further enhancements by linking evaluation results to outcomes. This first objective will be divided into outputs describing the winter and summer periods, with an air condition unit installed in the open office.

2) **The assessment of the indoor thermal environment in open office with foamed aluminium radiant ceiling panels and installed air-conditioning**

The further aim will be about the evaluation of the indoor thermal environment in open office with 16 persons for 3 years (2021, 2022, 2023), where in the office are installed foamed aluminium radiant panels. Two year operation of heating and cooling will be divided into winter and summer operation. In this assessment, the air-conditioning will be on; it is operational only with hygienic air exchange. The final results will be focused on its comparison.

3) **Determining the heating and cooling performance of foamed aluminium radiant ceiling panels during non air-conditioning operation**

For comparison of the same heating and cooling operation during a selected year, when there was no air condition unit installed in the open office. By evaluating the heating and cooling performances during the selected period, we will determine the efficiency and percentage utilization of the outputs.

4) **The assessment of the indoor thermal environment in open office with foamed aluminium radiant ceiling panels and without installed air-conditioning**

Next subchapter will evaluate the indoor thermal environment for 3 years (2017, 2018, 2019), when the air-conditioning was not installed in open offices. It will be divided the into heating and cooling operation. The final results will be evaluated and compared.

5) **The assessment of the indoor thermal environment in open office with foamed aluminium radiant ceiling panels and no installed air-conditioning during a weekend unoccupied operation**

The focus of this subchapter will be on assessing the indoor thermal environment during weekend operations, divided into heating and cooling periods without occupants, in an open office where air conditioning has not been installed. The primary objective is to observe the environmental behaviours during both summer and winter operations, devoid of human influence and without the functioning of air conditioning.

Input data

The open office is north-east oriented. The open office with foamed aluminium ceiling panels is divided into 3 heating and cooling circuits. In terms of performance and function, it is necessary to maintain a minimum speed of 0.15 m/s in the heating pipe; therefore, two different pipe dimensions were chosen: d18x1 and d12x1 - for higher capacities (circuits 2 and 3) Ø18/1, for lower capacities (circuit 1) Ø12/1. Each circuit is independently adjustable. The temperature gradient for heating was designed at 45/30 (circuit 1), 35/25 (circuit 2) and 35/26 (circuit 3). The temperature gradient for cooling was designed at 16/22.

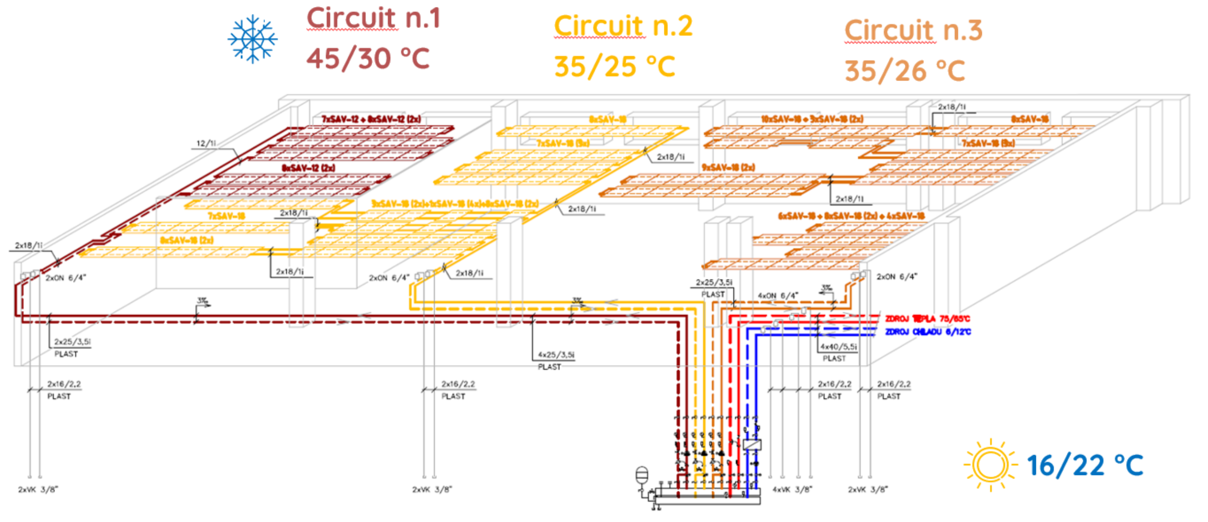


Fig. 5.3 Scheme of all three heating and cooling circuits for open office

Placement of measure instrument

The following section will describe the measured parameters of the indoor environment, measuring instruments, and measurement locations.

a) Measured parameters

- external air temperature (°C),
- indoor air temperature (°C),
- relative air humidity (%),
- supply water temperature to radiant panels (°C),
- return water temperature from radiant panels (°C).

b) Measuring instruments

- temperature sensor outer temperature Sensit NS110,
- ball sensor to measure internal spatial temperature Ni1000 / 5000
- dew Point Sensor QXA2000, Siemens,
- temperature sensor Temperature and return water Sensit,

c) Placement of measure instrument

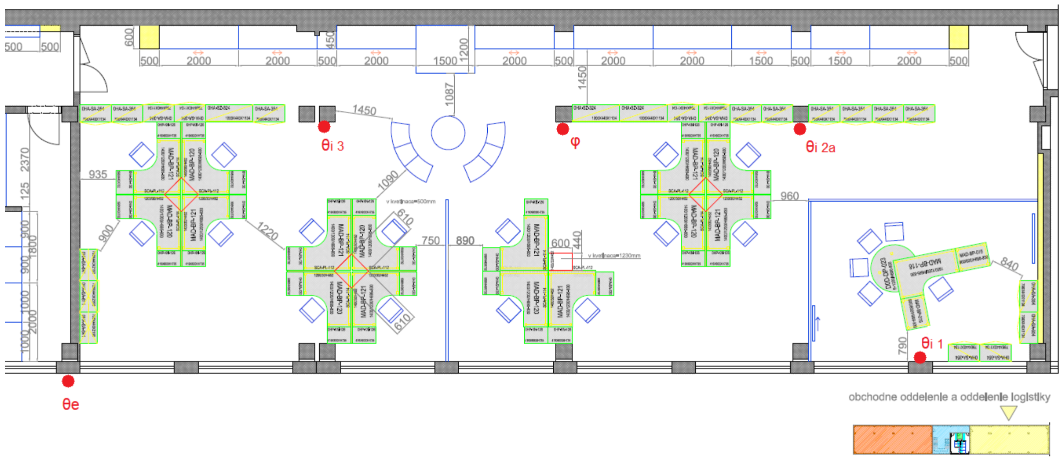


Fig. 5.4 Open office with radiant cooling/ heating and location of measurements ($\theta i_{1,2,3}$ operative air temperature, φ relative air humidity, θ_e external air temperature)

The assessment of the indoor thermal environment in open office with foamed aluminium radiant ceiling panels and installed air-conditioning

In the evaluation of indoor thermal environment for open office, we focused on dividing the measurement period into 2 years, but for the entire winter period, we did not have sufficient data for all months of both years. Therefore, we added another examined year, 2023.

The assessment of exterior and indoor air temperatures for both open office spaces

The indoor air temperatures were measured in three measuring points (1, 2A, 3) and for measuring point (2B) in the adjacent office, where convective heating - radiators was used.

Winter season measurements

The winter period was divided into the months of January to March, November, and December.

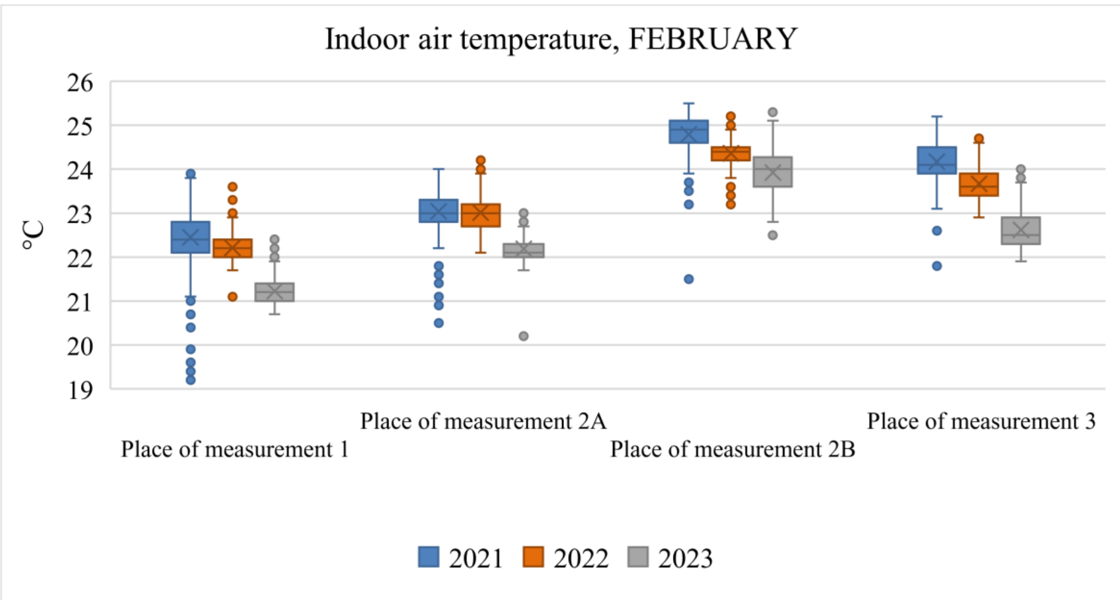
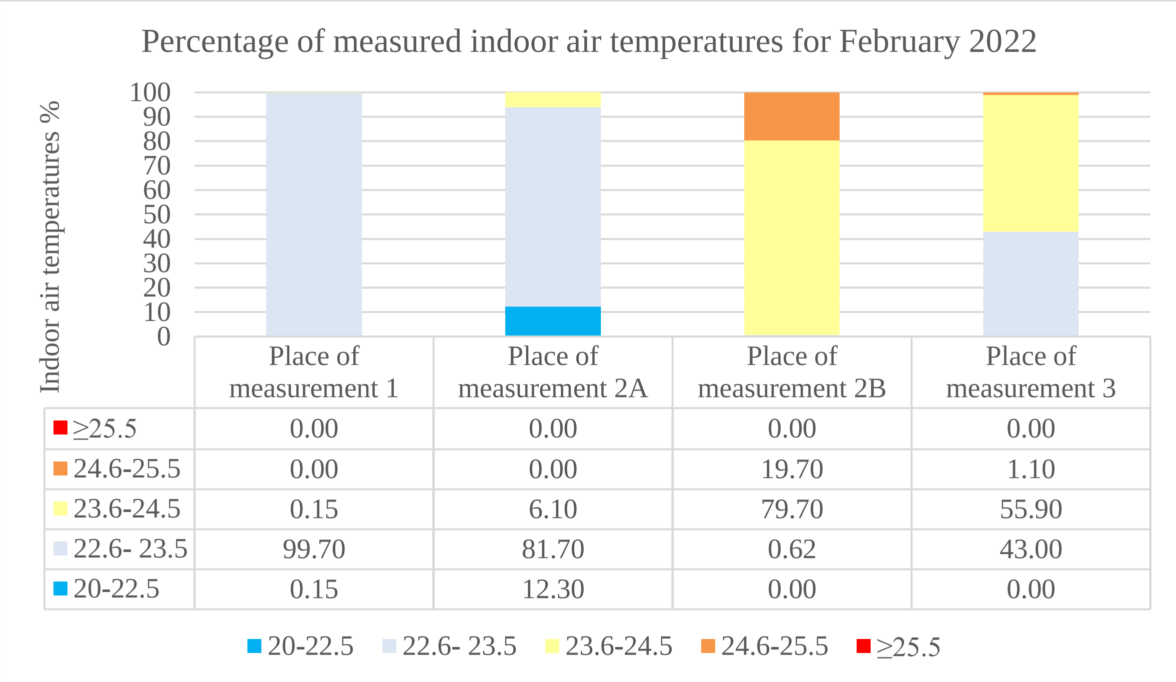


Fig. 5.5 Box plot graph for all measuring points for 3 years, winter season - February



	Place of measurement 1	Place of measurement 2A	Place of measurement 2B	Place of measurement 3
≥25.5	0.00	0.00	0.00	0.00
24.6-25.5	0.00	0.00	19.70	1.10
23.6-24.5	0.15	6.10	79.70	55.90
22.6- 23.5	99.70	81.70	0.62	43.00
20-22.5	0.15	12.30	0.00	0.00

Fig. 5.6 Classification of indoor air temperatures for each measurement location for the month of February

The last *Fig. 5.6* shows the classification of indoor air temperatures into individual ranges, for evaluating the percentage distribution of all measured values for the month of February 2022.

Summer season measurements

The next assessment for indoor air temperatures in open office was conducted for the summer period – the months of April, May, June, July, and August for the years 2021, 2022, and 2023.

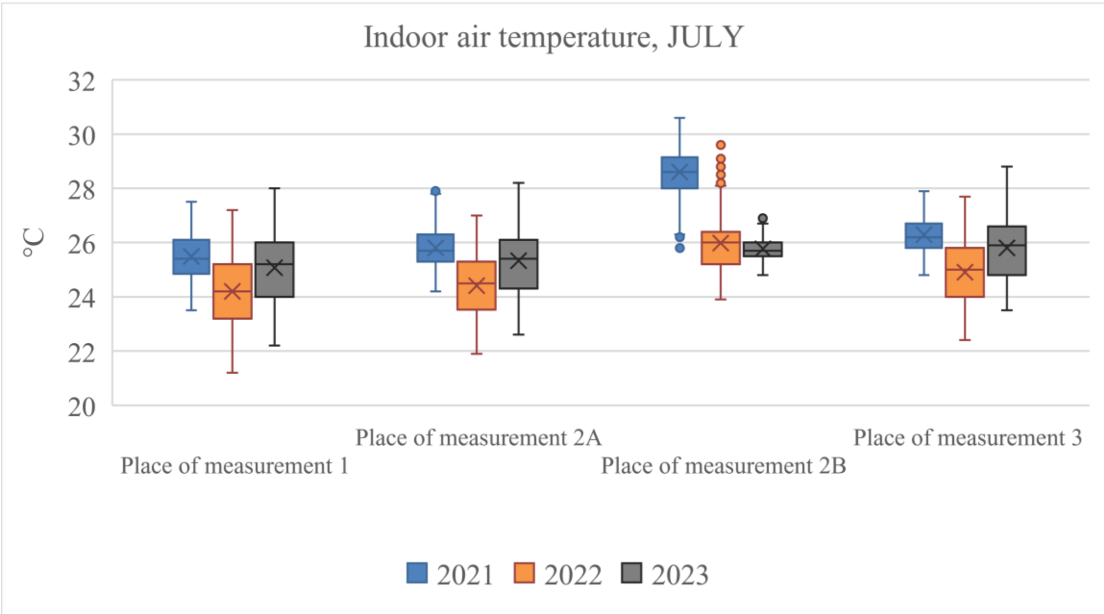
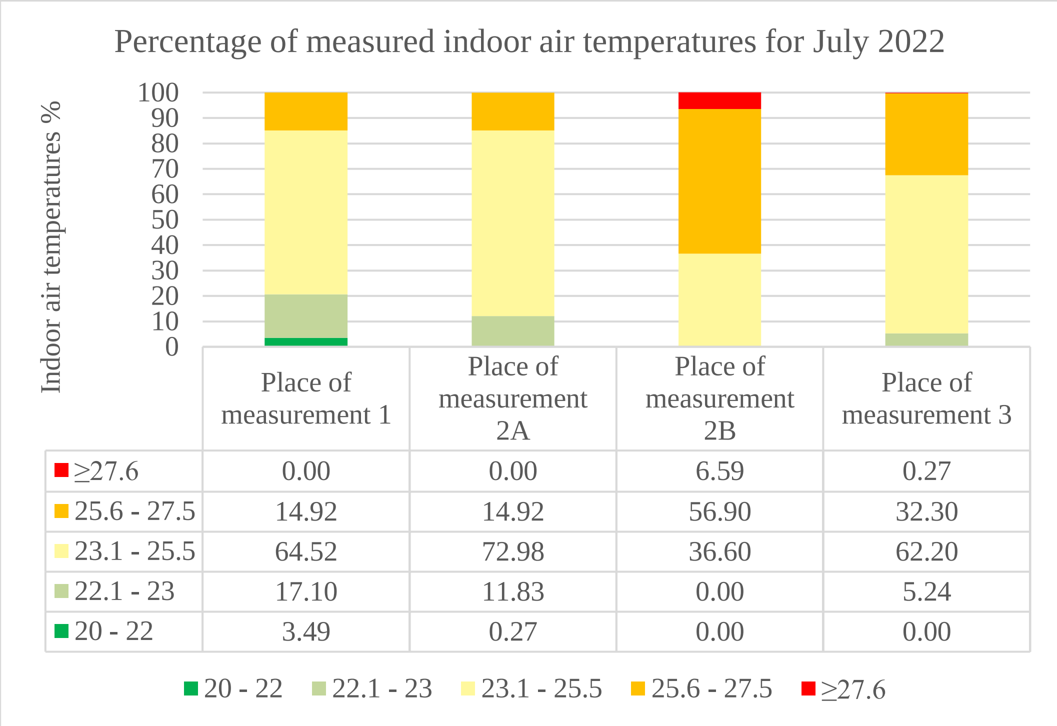


Fig. 5.7 Box plot graph for all measuring points for 3 years, summer season- July

A reference month for the summer period was selected from these three years – JULY, and its average monthly values were displayed for the 3 years. Radiant ceiling panels from foamed aluminium were used for cooling. We further analysed the detailed hourly measurements for the given summer month of July using a box plot, covering all three years and for the three zones within office space with radiant panels installed, as well as one zone from the opposite office space where radiant panels were not installed.



	Place of measurement 1	Place of measurement 2A	Place of measurement 2B	Place of measurement 3
≥27.6	0.00	0.00	6.59	0.27
25.6 - 27.5	14.92	14.92	56.90	32.30
23.1 - 25.5	64.52	72.98	36.60	62.20
22.1 - 23	17.10	11.83	0.00	5.24
20 - 22	3.49	0.27	0.00	0.00

Fig. 5.8 Classification of indoor air temperatures for each measurement location for the month of July

In the last *Fig. 5.8*, the figure shows the classification of indoor air temperatures into individual ranges, for evaluating the percentage distribution of all measured values for the month of July 2022.

The assessment of supply and return temperatures of the heat transfer medium for heating and cooling

In the following evaluation, we focused on displaying the results for supply and return temperatures of the heat transfer medium for heating and cooling over a period for 3 years. The years 2021, 2022, and 2023 were divided into winter and summer operating periods.

Winter season measurements

Subsequently, from the year 2022, we selected smaller time periods - one month for the winter period - February, and one month for the summer period - July.

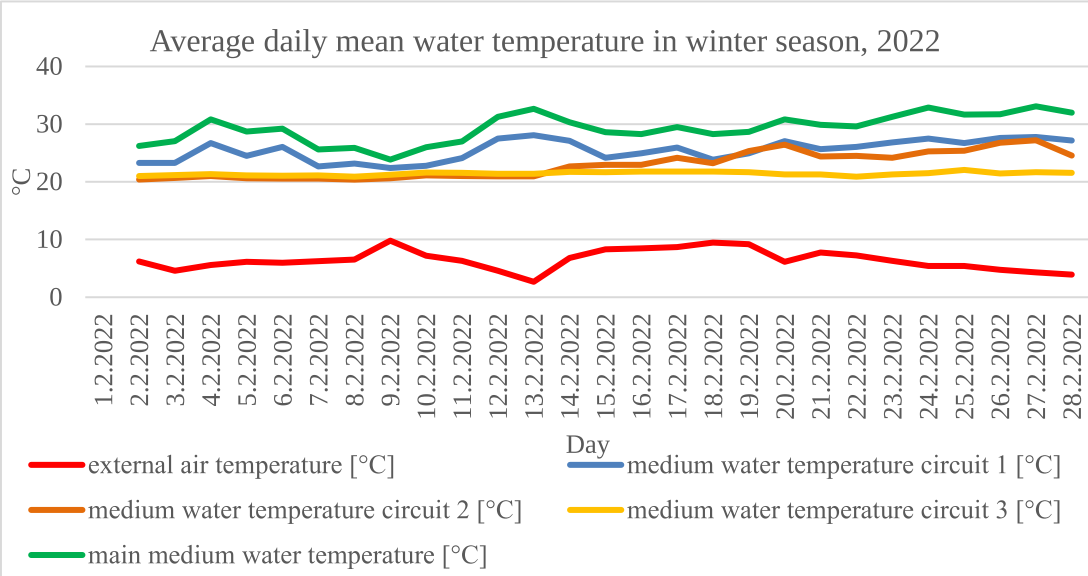


Fig. 5.9 Average daily mean water temperatures for February on 2022

In *Fig. 5.9* all 3 circuits average daily mean water temperatures are displayed for heating season – February on 2022.

Summer season measurements

Subsequently, from the year 2022, we selected smaller time periods - one month for the summer period – July. In *Fig. 5.10*, the average daily values of the mean water temperatures of the cooling medium during the summer are displayed for all cooling circuits, accompanied by the average daily outdoor air temperatures.

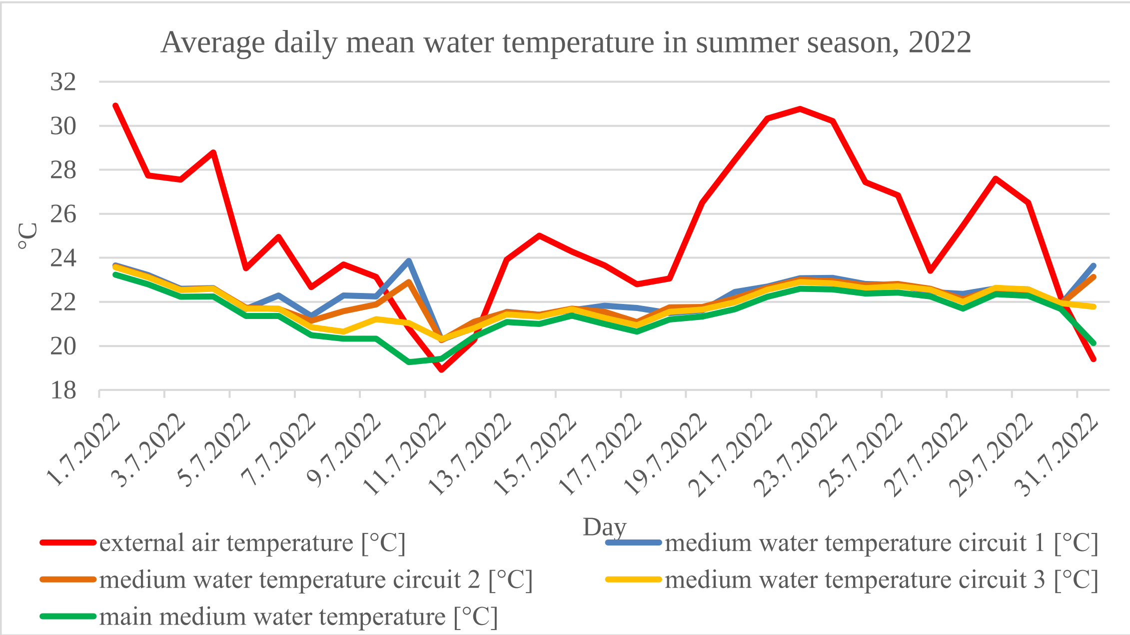


Fig. 5.10 Average daily mean water temperatures in July on 2022

The assessment of relative air humidity

The final evaluation for office space was the display of the results of relative air humidity for comparison in the summer and winter periods. In the following graph *Fig. 5.11*, all measured data of relative air humidity for the summer and winter periods of February and July over 3 years were evaluated.

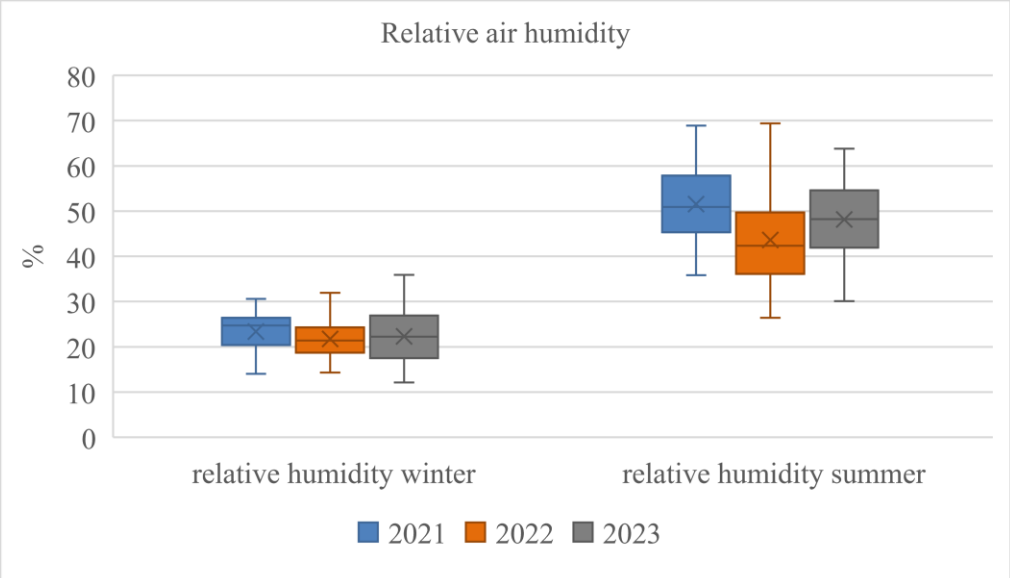


Fig. 5.11 Box plot graph of measured relative air humidity for 3 years

Main conclusions

Aluminium radiant panels designed for ceiling heating and cooling are highly efficient in ensuring thermal comfort throughout the year. They respond quickly to changes in the temperature of the heat transfer medium, which heats and cools the ceiling panel. The heating performance of all panels during the winter period reached a maximum of 30% in February 2022, specifically only in heating circuit 1. In 2018, the first circuit was also the most utilized, with a maximum average output of 37.8% in February. Cooling in 2022 and 2018 ranged from approximately 18 to 30% for all circuits. There is also no evidence of a significant difference in cooling performance between periods with and without the air conditioning unit.

Indoor air temperatures during the studied winter period for both compared variants remained within the optimal range of 20 to 24°C, with the differences between the application of the air conditioning unit and without it having little impact on the change in indoor air temperature in the offices. Similarly, during the summer period, indoor air temperatures ranged between the optimal limits of 23–27°C as set by the Ministry of Health Regulation No. 99/2016 Coll. Like in the winter period, indoor air temperatures were not significantly different during the study periods with and without the air conditioning unit, with temperatures without the air conditioning unit being on average 0.5 to 1°C higher. The air conditioning units in both offices were set only for forced air exchange, with supply air temperatures set in winter at 22-23°C and in summer at 24-25°C, or not significantly lower than the outside temperature—approximately

8 degrees. In the open office with applied heating elements, the indoor environment was comparably warmer than in the office with ceiling radiant panels. Indoor air temperatures during the winter period were approximately 24 to 25°C, and during the summer, they ranged between 23 to 29°C. In this office, it can be confirmed that the spaces were sometimes overheated, and during the summer period, indoor air temperatures were also higher than the optimal 27°C.

The average monthly mean temperatures of the supply heat transfer fluid for heating in the studied years, with and without the application of air conditioning units, did not differ significantly and had very similar trends in 2022 and 2018. It followed the pattern that the warmest heating circuit was number 1, followed by number 2, and lastly circuit number 3. In the evaluation of the average daily mean heating temperatures during the winter month of February, the temperatures in circuits 2 and 3 were lower than the average daily indoor air temperatures. The average monthly mean temperatures of the cooling heat transfer fluid were approximately the same in the studied years 2022 and 2018 for the summer period—July. Cooling was set to optimal requirements to ensure thermal comfort in the large office with radiant panels. The average daily exterior temperatures in 2022 ranged from 19.4 to 30.1°C, and for 2018, it was 17.6 to 28.2°C. The average mean temperatures of the cooling fluid during the studied years ranged from 19.3 to 23.2°C.

The evaluation of the average monthly values of relative humidity in all evaluated years during the winter period was below 30%, ranging from 21 to 24.9%. According to the Ministry of Health's regulation, the relative humidity of the air should be between 30 and 70%. Average monthly relative humidity in the years 2021 to 2023 for July ranged from 44.1 to 51.5%. For the years 2017 to 2019, the average relative humidity for July ranged from 47 to 48.5%. In summer, average relative humidity was within the range of 30 to 70%, as set by the Ministry of Health regulation.

6. ENERGY EVALUATION OF THERMALLY ACTIVE BUILDING SYSTEMS IN OFFICE BUILDING

The green Ecopoint offices in Košice consist of two office buildings. The investigated and assessed building was the second building, which is newer and was built in 2018. Building 2 has 6 floors and 2 underground floors. The object can be characterized as an office building with smaller multifunctional polyfunction and parking capacities in underground floors. The object has a basic layout of the letter L. A massive base formed by a bulk garage in two underground floors. The main - dominant 6-storey mass is an oriented longitudinal axis in the north - south direction and along the street of Magnetová is affiliated with a 5-storey narrower part.

Fig. 6.1 Picture of office buildings Ecopoint in Košice

Aim of the study

In the following chapter, interim goals for the administrative building in Košice, Ecopoint 2, are outlined. The aim of setting these two goals is to evaluate the energy data of consumed electrical energy, as well as the produced heat and cooling for one administrative building over two years (2020 and 2021).

An evaluation of consumed electric energy for office building Ecopoint 2

Electricity consumption is a significant indicator of how the building was utilized. Focusing on the source of heat and cooling – heat pumps – will provide insights into how they were designed and actually utilized. Evaluating the measured data on electricity consumption for the administrative building is a crucial step in managing energy efficiency and cost optimization. Another goal is to determine the coefficient of performance (COP) of the heat pumps.

An evaluation of produced heat and cold for office building Ecopoint 2

For the energy evaluation assessment, an additional goal is added to determine the produced heat and cooling over a 2-year period during both winter and summer seasons. These evaluations provide us with important insights into the performance and efficiency of heat pumps, aiding us in planning, optimizing, and managing these systems.

Input data

Two heat pumps, BLUE BOX TETRIS W/HP, are used for heating and cooling the 6 above-ground floors of the administrative building. This facility serves administrative purposes. TABS pipes embedded in the concrete structure either heat or cool according to the desired room temperature, which is centrally set. Thermostats are also located in individual zones to monitor the indoor air temperature in the spaces.

Heat source: the need for heat will be secured from its own heat source - water pump water - natural collector, placed in engine room at the 2. underground floor. As the heat source have been designed two heat pumps water - brine from geothermal boreholes BLUE BOX

TETRIS W / HP 10.2 with nominal heat power of condenser 2. 108.54 = 217.08 kW at a temperature drop of water on the capacitor side 35/30 °C. Heating and cooling 2 branches, north and south are designed for TABS. The main heating (cooling) system are active a large-scale system of Rehau F 17/2 mm plastic ceilings 62 mm from the lower edge of 150 mm discharge ceiling (ceiling 1. NP) and 90 mm (other floor ceilings)).

Fig. 6.2 Heat pumps in Ecopoint 2

The core should have minimum temperature in winter 21 ° C and in summer maximum temperature 25 ° C. Earth Collectors. Geothermal depthrills: drill depth around 130 m, distance between drills 10 m, number of drills 30, plastic pipes. Volume flow for one drill is 1.692 m3 / h, total flow (30) boreholes 50.76 m^3/h.

Placement of measure instruments

a) Measurement parameters

- electricity consumption (kWh)
- generated heat (MWh)
- generated cold (MWh)

b) Measuring instruments

- electrometer Schneider Electric iEM32235

Fig. 6.3 Electrometer Schneider Electric in Ecopoint 2

- calorimetric heat generation counter KAMSTRUP MULTICAL 602C0677001577
- calorimetric cold generation counter KAMSTRUP MULTICAL 602C0677001519


Fig. 6.4 Calorimetric heat and cold generation counter in Ecopoint 2

An evaluation of consumed electric energy for office building Ecopoint 2

In the following section, the evaluation of the two-year electricity consumption for the operation of heat pumps and supporting technology for the years 2020 and 2021 is presented.

Tab. 6.1 Electricity evaluation of Ecopoint 2 for 2021

2021

ECOPOINT 2 Schneider Electric iEM3135	Electricity consumption kWh	Consumption of heat pump electricity without support technology kWh	Maximum electric power of heat pumps (2pcs) kWh	Utilisation of heat pumps %	Heat production kWh	COP
January	10 274.2	10051.97	30891	33	40 000.0	3.98
February	9 454.686	9232.46	27901	33	37 000.0	4.01
March	7 419.781	7197.55	30891	23	26 800.0	3.72
April	4 439.658	4217.43	29894	14	14 000.0	3.32
May	980.569	758.34	30891	2	2 100.0	2.77
June	215.477	-	-	-	-	-
July	223.314	-	-	-	-	-
August	227.901	-	-	-	-	-
September*	429.64	207.41	29894	0,7	700.0	3.37
OctobeR	2 674.468	2452.24	30891	8	9 400.0	3.83
November	5 193.563	4971.33	29894	17	21 100.0	4.24
December	9 332.333	9110.10	30891	29	37 300.0	4.09
	50 865.59					

*part quantified for heating

The assessment of an evaluation of produced heat and cold for office building Ecopoint 2

In the following evaluations, using calorimetric meters KAMSTRUP MULTICAL, we were able to read the monthly heat and cooling produced for the examined operational periods in the years 2020 and 2021. This allowed us to subsequently assess the operation of the heat pumps for the evaluated summer and winter periods.

Produced heat

Tab. 6.2 Evaluation of produced heat for Ecopoint 2 for year 2021

2021

ECOPOINT 2 Kamstrup Multical	Heat production MWh	Hours of operation of heat pumps (2pcs) h	Maximum heat output from real hourly operation of heat pumps (2pcs) MWh	An hourly utilization of heat pumps %	Maximum monthly heat output of heat pumps (2pcs) MWh	Utilization of heat pumps %
January	40.0	1354	147	27	162	25
February	37.0	1176	128	29	146	25
March	26.8	1212	132	20	162	17
April	14.0	930	101	14	156	9
May	2.1	155	17	12	162	1
June	0.0	0	-	-	-	-
July	0.0	0	-	-	-	-
August	0.0	0	-	-	-	-
September	0.7	36	4	18	156	0,4
October	9.4	471	51	18	162	6
November	21.1	623	68	31	156	13
December	37.3	1254	136	27	162	23
	188.4	7211				

Produced cold

Tab. 6.3 Evaluation of produced cold for Ecopoint 2 for year 2021

2021

ECOPOINT 2 Schneider Electric iEM3135	Cold production MWh	Maximum cooling output of heat pumps (2pcs) MWh	Utilization of heat pumps %	Hours of operation of heat pumps h
January	0.0	0	0	0
February	0.0	0	0	0
March	0.0	0	0	0
April	0.0	0	0	0
May	0.0	0	0	0
June	18.0	-	-	0
July	20.4	-	-	0
August	8.5	-	-	0
September	2.1	-	-	0
October	0.0	0	0	0
November	0.0	0	0	0
December	0.0	0	0	0
	49.0			

Partial conclusion

As a partial conclusion of the established goal for the energy evaluation of thermally activated building structures in the Ecopoint 2 administrative building with heat pumps, the percentage utilization of the heat pumps based on electrical energy and thermal input was determined (the electricity consumption for supporting technology was included in the electricity consumption results, as there was no separate electrometer installed).

The heat pumps operated at a maximum of 33% in terms of electrical energy and a maximum of 25% in terms of thermal output during the studied years. Passive cooling during the summer months resulted in saved electricity production, as the cooling of the entire building was achieved using chilled water from the ground through 30 drills.

Transient periods in 2020 and 2021 were detailed in the evaluation chapter, where the amount of heat and cooling produced in each month was quantified. In 2020, heating and cooling were active in May, while in 2021, September was the active month for these operations.

7. RECOMMENDATIONS AND BENEFITS FOR SCIENCE AND PRACTISE

Recommendations and benefits for science

Design calculations of heat flux for radiant ceiling panels with phase change materials (PCMs)

- **Innovative technological advancement:** new materials used in radiant systems require extensive research to effectively utilize and improve indoor environments while reducing operational costs.
- **Development of standards:** research findings contribute to the development of building codes, standards, and regulations related to the design of radiant ceiling panels with phase change materials (PCM).
- **Design optimization:** insights from research can aid in optimizing the design and operation of radiant systems with installed ceiling panels incorporating PCM.
- **Energy efficiency:** research has demonstrated that these radiant panels exhibit properties similar to TABS (Thermally Active Building Systems), which can be leveraged during retrofitting projects. PCM materials can extend operational peak hours beyond working hours.

Evaluation of indoor thermal environment with the radiant heating and cooling system through a foamed aluminium radiant ceiling panels

- **Innovative technological advancement:** similarly to the first goal, new materials not commonly manufactured were explored. Radiant panels made from foamed aluminium demonstrated excellent properties for ensuring indoor environmental quality in an open office.

- **Design optimization:** research findings published in the dissertation thesis indicate that the number and performance of radiant panels need redesign. The performance of radiant panels was oversized, and a less number of panels were sufficient for the open office space. Insights into foamed aluminium ceiling panels contribute to improving future performance design and optimizing heat and cold distribution.
- **Thermal comfort for workers**: research demonstrated that foamed aluminium radiant panels provide quality thermal comfort in open office spaces.
- **Financial resources**: initial investment costs are reduced because it was found that a smaller number of radiant panels are needed for heating and cooling. Operating costs are also lower compared to other heating methods, as a small amount of heat or cold is sufficient to heat up or cool down foamed aluminium radiant panels. Its rapid response and good thermal conductivity are additional benefits demonstrated in the dissertation thesis.

Energy evaluation of thermally active building systems in office building

- **Design and operation optimization:** evaluations of heat and cold production, as well as electricity consumption, analysed for the office building utilizing heat pumps, showed excellent optimization. The favourable conditions of geothermal wells for cooling were utilized through passive cooling methods.
- **Cost savings:** these were notably evident in the heat pump's COP (Coefficient of Performance) and during passive cooling in summer when the heat pumps were turned off. Improvements in energy efficiency and operational cost reduction offered by radiant technologies provide potential cost savings for building operators and contribute to economic sustainability.

Recommendations and benefits for practice

- **Innovative technological contribution**: radiant ceiling panels with innovative materials hold significant promise for future designs of radiant systems used for heating and cooling. This represents a new potential for further development and future applications.
- **Knowledge sharing**: research findings enable knowledge sharing and collaboration among researchers, engineers, architects, and industry stakeholders, fostering continuous innovation and advancement in radiant heating and cooling technologies.
- **Indoor environmental quality**: radiant systems ensure optimal thermal environments in buildings. In the second objective, assessment of relative humidity during winter cooling revealed critical values below 20% with aluminium foam radiant panels.
- **Faster response to temperature changes:** aluminium foam radiant ceiling panels exhibit faster response to heating and cooling demands, allowing quicker achievement of desired room temperatures.
- **Energy and financial savings**: all three radiant systems demonstrate excellent energy savings and associated operational cost reductions. Panels with PCM materials show

reduced peak demand and off-peak shifting capabilities. Aluminium foam radiant panels offer large heating and cooling surfaces that heat up and cool down rapidly. It has been demonstrated that the current panel design only utilizes 20% in one of the three circuits. Regarding TABS systems with heat pumps, they were effectively utilized during summer for passive cooling using chilled water from underground floors, minimizing electrical energy consumption by the heat pumps. Advances in radiant systems contribute to sustainability efforts through promoting renewable energy sources, reducing greenhouse gas emissions, and enhancing overall energy efficiency in buildings.

8. CONCLUSION

Low temperature heating and high temperature cooling are classified among radiant systems that have increasingly been applied in building construction in recent years. Regarding the use of renewable energy sources alongside radiant systems, heat pumps are currently the predominant source used year-round for both heating and cooling. Research has shown that these systems offer numerous advantages, including increased user comfort, reduced energy costs, and better temperature control across different building zones.

One of the latest findings in research indicates that radiant systems are evolving, exploring innovative materials capable of significantly improving thermal stability within indoor environments. They also aim to reduce peak energy demands and shift them outside of working hours during the summer. A newly studied material, Phase Change Material (PCM), holds promise for heating and cooling in renovated buildings. Research focuses primarily on cooling needs, with radiant ceiling panels incorporating PCM materials representing a potential innovative solution. Indoor environmental quality in buildings is predominantly perceived subjectively, but it is crucial to adhere to optimal values set by health ministry regulations for indoor air temperature, air circulation, and relative humidity to minimize dissatisfaction. Radiant systems can provide optimal conditions if responsibly designed and new technologies are thoroughly researched.

Thermally active building systems (TABS) combined with heat pumps demonstrate a suitable integration of radiant systems with renewable energy sources, enabling year-round heating and cooling. Utilizing energy from underground sources during the summer is cost-effective when spaces can be cooled through passive operation, allowing heat pumps to remain off. Future trends indicate that radiant systems will play an increasingly significant role in sustainable construction and energy efficiency. Further research and development in this field should focus on optimizing design methodologies, improving materials and technologies, and expanding opportunities for integrating renewable energy sources. In conclusion, radiant systems represent advanced and promising solutions that contribute to improving indoor environmental quality, reducing building energy demands, and supporting sustainable development. The latest research findings confirm their potential and underscore the need to continue their implementation and further investigation.

Zoznam publikačnej činnosti Autor: Švarcová, Eva

V2 Vedecký výstup publikačnej činnosti ako časť editovanej knihy alebo zborníka

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