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Comparative analysis of energy demand at an equal operative temperature in the case of radiator and low-temperature radiant heating

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ABSTRACT

Despite energy-saving efforts heating still represents an important share in the energy balance of buildings. Low-temperature radiant heating systems are considered advantageous in terms of energy saving and thermal comfort. The goal of the performed research was to compare the energy demand at equal operative temperatures between “low-temperature radiant heating” and “radiator heating”. 432 room models were developed in different geometries, envelopes, windows-to-wall ratios, and indoor air set-point temperatures while the variations of radiant and operative temperatures were determined. The surplus of energy in the case of radiator heating to obtain similar operative temperatures was calculated, and the heat released and heat losses of radiant heating were determined. The average surplus of heat in the case of radiator heating is 3.07 %. Furthermore, it was found that the total energy demand by low-temperature radiant heating exceeds in all 432 analysed cases of radiator heating because of the huge heat losses (40.71 % on average), which are generated by the embedded heating layers in external building elements. The energy demand for heating in the case of radiant heating systems was 1.69 %–8.62 % higher than radiator heating.

1. Introduction

Decarbonisation of the building energy sector is one of the most important goals in developed countries and it is key to achieving net zero carbon emission targets by 2050 [1]. Different scenarios have been elaborated to develop national and transnational roadmaps to achieve global emission reduction targets [2]. Yan et al. evaluated the progress of operational decarbonisation in residential buildings in the two largest emitters, China and India, during the 21st century [3]. It was found that operational carbon intensity increased in the mentioned countries at 1.4 % and 2.5 % per year from 2000 to 2020, respectively, while collectively decarbonizing 1498.3 and 399.7 $MtCO_2$ of residential building operations in the same two decades [3].

Nearly zero energy buildings (NZEB) have an important contribution to meeting the decarbonisation goals of the building sector, however, the renewal rate of the existing building stock is extremely low (about 0.5 % in Hungary) [4]. According to recent studies

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carried out to analyse the energy use in buildings situated in temperate climates, heating represents the largest share being estimated to be 30%–50 % of total energy consumption [5,6]. Therefore, besides efficient thermal insulation of envelopes, buildings should use clean and renewable energy sources [7]. Professionals can choose from several solutions when designing a building's heating system. One possible solution is radiator heating. In this case, a heater is placed in the room (most often under the window), the size of which is chosen so that the heat delivered covers the heat demand at certain design supply and return temperatures. Most heat is released by convection (60%–65 %) and less by radiation (35%–40 %). Another heating option is low-temperature radiant heating with embedded hydronic circuits. In this case, the warm water temperature can be lowered (having a higher heating surface) and the share of heat released by radiation is higher (40%–50 % in the case of floor heating, 50%–60 % in the case of wall heating and 70–80 % in the case of ceiling heating). Lower supply and return temperatures allow higher energy performance of heating systems and heat pumps can be used efficiently.

D'Agostino et al. found that heat pumps are the most commonly used technology for heating and domestic hot water (DHW) preparation in exemplary NZEB buildings across the European Union [8]. Low-temperature radiant heating can be the optimal solution for such systems, providing appropriate thermal comfort in indoor spaces [9]. Oravec et al. performed a comparative study of six representative radiant wall, floor, and ceiling systems in terms of their thermal output, area of the heating surface required, controllability, short-term and long-term energy storage, suitability for installation in existing buildings, and construction costs [10]. It was revealed that floor heating performed most consistently in all the aspects evaluated indicating its universal use.

According to Rhee et al. , radiant floor heating systems are installed in almost all residential buildings in Korea, 85 % of rural houses in northern China, and 30%–50 % of new residential buildings in Germany, Austria, and Denmark [11]. Many studies have revealed that low-temperature radiant heating systems can save between 10 and 30 % of energy and provide better thermal comfort than all-air heating systems [12]. Bojic et al. performed energy, environmental, and economic performance investigations of floor, wall, ceiling, and floor-and-ceiling heating [13]. It was found that although the combined floor and ceiling heating system has the lowest exergy efficiency, it has the best performance: the lowest energy consumption, operation costs, and the nominal power of the boiler. It should be mentioned that the embedded heating layers can operate as thermal barriers. Krajcík et al. reviewed the studies related to the energy efficiency of thermal barriers [14]. The authors formulated a cautious summary regarding energy savings and emphasized the need for measurements. However, Li et al. demonstrated that in the case of radiant ceiling panels, the upward heat flux from the panels can reach 30–40 % of the water heating capacity [15]. During operation, this would translate into heat losses in the heating system.

In the case of embedded radiant heating systems, inserting a layer with higher temperature in the external building structure (wall, floor, ceiling), the heat flux on the outer side of the building element will exceed the heat losses of that building element in the case of convective heating systems. These heat losses may be comparable or, in special cases, even exceed the heat released by the radiant surface to the heated space [16]. The heat losses of the system depend on the chosen supply/return temperatures, while the operating temperatures of the system are chosen depending on the heat demand of the rooms. Shin et al. tried to find the optimal temperatures for floor heating [17]. Krajcík et al. analysed thoroughly the wall heating systems [18]. Safizadeh et al. provided a comprehensive analysis of ceiling heating [19].

The heating capacity and the heat released by low-temperature radiant surfaces depend on the filling materials between the pipes, surface materials above the pipes, material of the pipes, and the surface heat transfer coefficient [20,21]. Numerous studies analysed the value of the surface heat transfer coefficient of different radiant surfaces. Karakoyun et al. performed an artificial neural network investigation is carried out to predict heat transfer characteristics over a heated radiant ceiling [22]. Koca et al. estimated experimentally the values of heat transfer coefficients for radiant wall heating panels [23]. Acikgoz et al. experimentally determined the heat transfer characteristics of an underfloor heating system in a test chamber [24]. Koca and Cetin called attention to the importance of experiments showing that measured values of heat transfer coefficients differ from the recommended values in standards [25]. Shinoda et al. provided an extensive literature review of articles, standards, and guidelines that focus on the heat transfer coefficients of cooled/heated surfaces [26]. They found larger deviations and prediction errors in the total and convective heat transfer values than in radiant heat transfer.

Summarizing the reviewed literature, it can be stated that comprehensive studies have been performed and published related to low-temperature radiant heating systems. Ceiling-, wall- and floor heating are widely used especially in well-insulated new buildings. Because of the large heating surfaces, the operation temperature of circulated warm water can be lower compared with traditional radiators or other convective heating systems. In the case of similar heating modes, a lower operation temperature will lead to lower heat losses. But what will happen in the case of different heating system types? Most studies emphasized the advantages of better thermal comfort and lower energy consumption. It should be stated that in a heated room with a certain heat demand during the heating process, the mean radiant temperature will be higher than in a room convectively heated (all air systems, convectors, radiators). On the other side, in the case of embedded radiant heating systems, the heat losses may decrease the energy efficiency of the system. There is no information about the total energy demand by low-temperature radiant heating systems and the total energy demand in the case of heating systems with radiators, providing similar operative temperatures in a room. Nevertheless, this is a cardinal question when the goal is energy saving and decarbonisation of buildings.

The research aims to determine the surplus of energy demand by heating systems with radiators to provide in a room the same operative temperature as the low-temperature radiant heating system provides. Furthermore, the effects of the indoor air set point temperature, the room geometry, the thermal performances of the envelope, and the windows-to-wall ratio on this energy demand are investigated. The obtained results are of utmost importance to have a clear image of the energy consumption of these two heating system types.

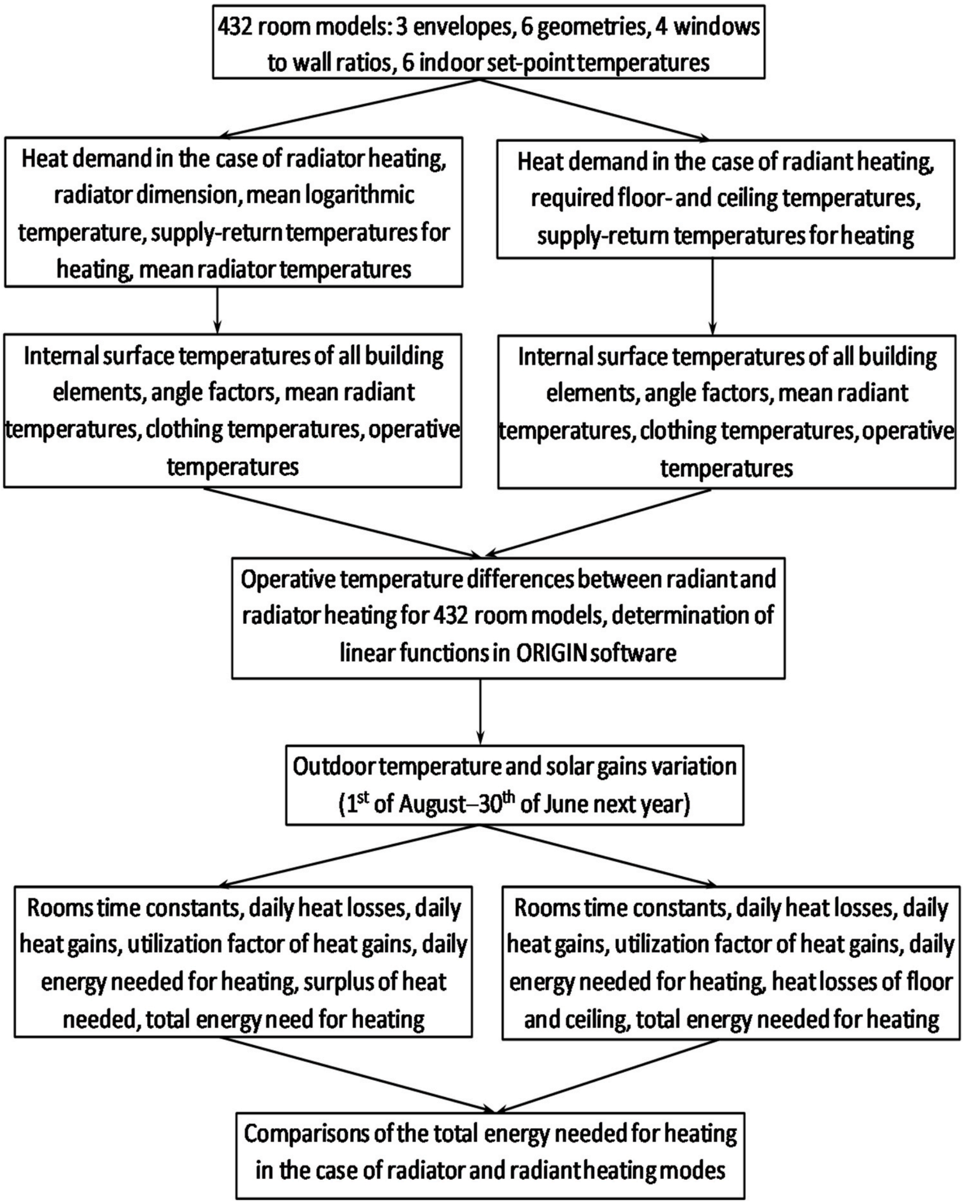

Fig. 1. Flowchart of performed research.

2. Research method

Taking into account the thermal inertia of buildings and analysed rooms, energy calculations have been done on a "daily basis" dynamically. The daily values of climatic parameters have been determined using the hourly temperatures and incident solar radiations on vertical surfaces given for energy performance calculations in Hungary.

The research was designed and performed according to the following steps.

1) Calculations of heat demand for considered rooms (6 geometries × 4 WWRs × 3 envelopes × 6 indoor temperatures = 432 cases for radiator and 432 cases for radiant heating);
2) Dimensioning of radiators according to the product catalogue [27]. In all cases, 22 K type 600 mm height radiators have been chosen;
3) Determination of the supply and return temperatures for radiator heating;
4) Determination of floor and ceiling surface temperatures in the case of radiant heating;

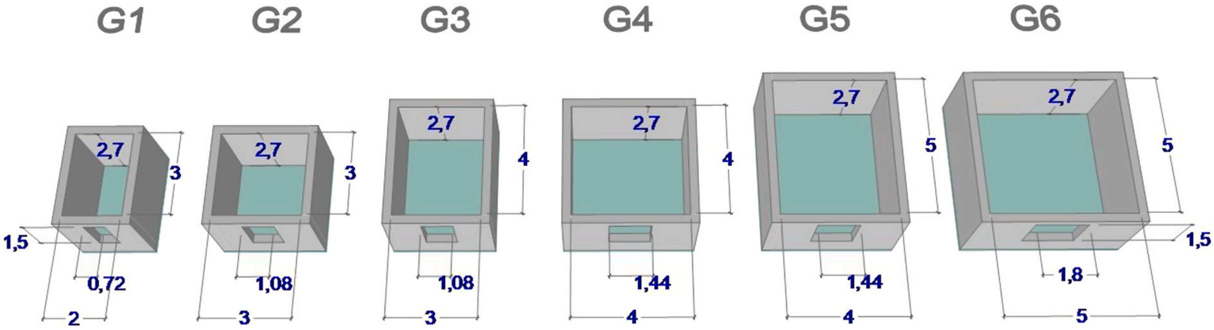

Fig. 2. Room geometry models.

Table 1
Characteristics of external building elements and the ACH values.

Code/Source	Building element	U, [W/m^{2}K]	ACH, [1/h]
E1 [30],	External wall	0.70	0.7
	Floor	0.70	
	Ceiling	0.40	
	Window	2.00	
E2 [31],	External wall	0.44	0.5
	Floor	0.47	
	Ceiling	0.29	
	Window	1.60	
E3 [32],	External wall	0.23	0.5
	Floor	0.25	
	Ceiling	0.16	
	Window	1.15	

5) Determination of the internal surface temperatures for all external building elements (the surface temperatures of the internal walls have been considered equal to the set-point temperature). The surface temperatures (building elements and heating surfaces) have been calculated for seven different external temperatures: −15 °C; −10 °C, −5 °C; 0 °C; +5 °C; +10 °C; +15 °C.
6) Considering one occupant sitting in the middle of the room facing the window the angle factors have been determined for 24 different cases (6 geometries × 4 WWRs), and the mean radiant temperatures have been determined in all 6048 analysed cases (432 × 7 external temperatures = 3024 cases for radiator and similarly 432 × 7 = 3024 cases for radiant heating);
7) Calculations of the convective heat transfer coefficient around the occupant, the clothing temperatures and the radiant heat transfer coefficients;
8) Determination of the operative temperatures in all 6048 cases;
9) Determination of the differences between operative temperatures;
10) Description of the differences between the operative temperatures with linear functions (mean $R^2 = 0.99928$, minimum $R^2 = 0.93773$);
11) Determination of heat gains and daily utilization factors;
12) Determination of the energy consumed by radiator heating and the surplus of energy demand in 432 cases;
13) Determination of the energy demand for heating in the case of combined floor and ceiling heating and the heat losses;
14) Analysis and discussion of the energy consumption.

The flowchart of the performed research is presented in Fig. 1.

2.1. Geometry model and boundary conditions

The energy demand for heating strongly depends on the position of a room in the building, namely how many external building elements should be taken into account. In a multifamily building, a room can have only one external building element. The heat demand of such a room is lower than the heat demand of a room placed under the attic or above the cellar. In this research, a room placed in the corner of a single-family house with a floor slab above the unheated cellar and an unheated attic above the ceiling was chosen and analysed.

The internal height is 2.7 m in all cases. Six different geometries of the net floor area are considered: 2.0m × 3.0m (G1); 3.0m × 3.0m (G2); 3.0m × 4.0m (G3); 4.0m × 4.0m (G4); 4.0m × 5.0m (G5), and 5.0m × 5.0m (G6). The room geometry of residential buildings is certainly diverse, but this study aimed to analyse both small and large-sized rooms. Thermal comfort standard EN 16798-1 recommends the minimum value of the indoor operative temperature in the heating season (20 °C, in the case of II comfort category),

[28]. However, depending on the occupants' comfort needs different indoor temperatures ought to be considered. On one of the external walls, a 1.5 m height window is placed. The width of windows is determined depending on the windows-to-wall (WWR) ratio assumed. The required minimum window dimension is recommended depending on natural lighting conditions, [29]. Four different WWRs were considered: 20 % (W1), 30 % (W2), 40 % (W3), and 50 % (W4). The height of the parapet wall under the window is 0.9 m in all cases. In the case of radiator heating, the radiator is always placed under the window and the length of the radiator is chosen to be equal or almost equal (depending on the product) with the width of the window (Fig. 2).

The supply and return temperatures were determined depending on the heat demand of the room. In our study, we have taken into account six different indoor set-point temperatures: 20 °C (T1); 21 °C (T2); 22 °C (T3); 23 °C (T4); 24 °C (T5), and 25 °C (T6). Finally, we consider three different thermal performances for the external building elements. The chosen external building structures meet the requirements fixed in standards or decrees in Hungary in different years: 2002 (envelope code: E1), 2012 (envelope code: E2) and 2022 (envelope code: E3). The overall heat transfer coefficients and the air change rates (ACH) assumed in the mentioned cases are shown in Table 1.

Taking into account all these parameters we have 432 different cases. Each analysed room has its own code. For example, the code E1G2W3T4 means that a room with 3.0m × 3.0m × 2.7m geometry, 40 % WWR, 23 °C is considered. The U values of the external building elements are given in Table 1 (E1). The ACH is 0.7 1/h.

In the case of radiant heating, floor heating in combination with ceiling heating was taken into account, since according to previous publications this heating mode gave the best results [13].

The supply and return temperatures of the heating systems were determined by taking into account the heat demand of the rooms. The calculation methodology is presented in Appendix 1 (A1, Eqs. A6 and A7). In the case of radiator heating a temperature drop of 20K was assumed. In the case of floor and ceiling heating the inner surface temperatures of building elements were determined from the heat demand of the rooms as well as considering the surface heat transfer coefficients given in the literature.

2.2. Calculation procedure

2.2.1. Energy demand for heating

The energy demand for heating in the whole heating season can be determined using eq. (1):

$$E_h = \int_{j=1}^{j=N} 0.024 \cdot \left[H\left(t_i - t_{ej}\right) - \eta_j\left(\dot{Q}_i + \dot{Q}_{sj}\right)\right], [\text{kWh}] \tag{1}$$

where N is the number of heating days; H – heat loss coefficient of the room, [W/K]; t_i – indoor set point temperature, [°C]; t_e – mean outdoor temperature of heating day j, [°C]; $\dot{Q}_i$ – mean value of indoor heat gains in a heating day, [W]; $\dot{Q}_{sj}$– mean value of solar heat gains in the j heating day, [W]; η_j – utilization factor of heat gains in j heating day. The energy calculations have been done assuming the mean indoor heat gains of 5.0 W/m^2, [32].

The heat storage capacity (C) and the room time constant (τ) have been determined using the relations and methodology given in standard EN ISO 52016-1 [33]. The utilization factor of heat gains can be calculated for each heating day using eq. (2) [34]:

$$\eta_H = 1 - e^{\frac{-k}{\gamma_H - D}} \tag{2}$$

where γ_H is the ratio between daily heat gains and heat losses of the room; k and D are correlation coefficients. For these coefficients, Yohanis and Norton proposed the following relations [34]:

$$k = 1.0785 + 0.0041\tau - 6 \times 10^{-7} \tag{3}$$

$$D = -0.0087 - 0.007 + 7 \times 10^{-8}\tau^2 \tag{4}$$

2.2.2. Operative temperature

The operative temperature was calculated depending on the indoor set-point temperature and mean radiant temperature [35]:

$$t_o = \frac{h_c \cdot t_i + h_r \cdot \bar{t}_r}{h_c + h_r} \ [^\circ\text{C}] \tag{5}$$

where $\cdot\bar{t}_r$ is the mean radiant temperature in the room, [°C]; h_c – convective heat transfer coefficient of the human body, [W/m^{2}K]; h_r – radiant heat transfer coefficient of the human body, [W/m^{2}K].

Since there is no forced air circulation in the analysed rooms, the convective heat transfer coefficient depends on the temperature difference between the occupant's clothing surface temperature and indoor set-point temperature [35]:

$$h_c = 2.38 \cdot (t_{cl} - t_i)^{0.25} \ [\text{W}/\text{m}^2\text{K}] \tag{6}$$

The radiant heat transfer coefficient can be determined depending on the temperature difference between the occupant's clothing surface temperature and indoor set-point temperature [36]:

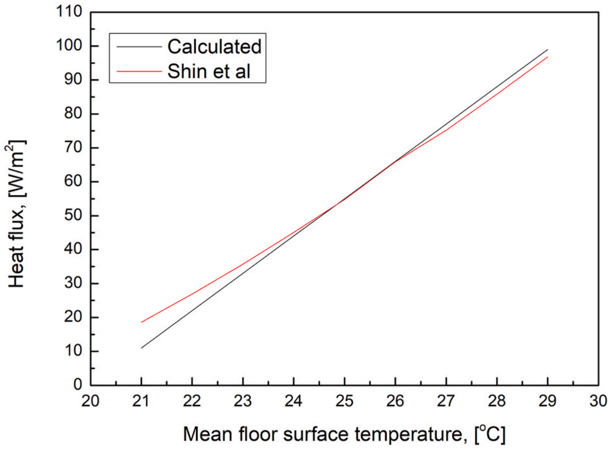

Fig. 3. Heat flux depending on the floor temperature.

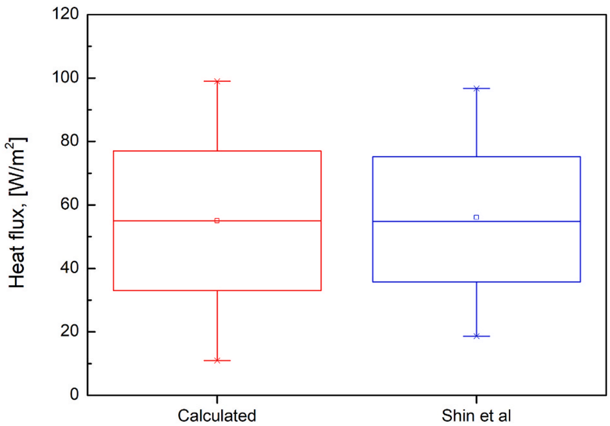

Fig. 4. Box chart of calculated and measured [17] heat flux values.

$$h_r = 5.67 \cdot 10^{-8} \cdot \varepsilon \cdot \frac{A_r}{A_{Du}} \cdot \frac{(t_{cl}+273)^4 - (\bar{t}_r+273)^4}{(t_{cl}-\bar{t}_r)} \; [\mathrm{W/m^2K}] \tag{7}$$

where A_r is the effective radiant surface of the human body, [m^2]; A_{Du} – Du Bois surface of the human body, [m^2]; ε - emission coefficient of clothing surface and human body uncovered by clothing.

The ratio A_r/A_{Du} is 0.7 for a sitting person, while the emission coefficient ε was assumed 0.9.

The clothing temperature was determined using eq. (8) [35]:

$$t_{cl} = 35.7 - 0.028(M-W)I_{cl} \cdot$$

$$\left\{h_r f_{cl} 10^{-8}\left[(t_{cl}+273)^4 - (\bar{t}_r+273)^4\right] + f_{cl} h_c (t_{cl}-t_i)\right\}, [^\circ\mathrm{C}] \tag{8}$$

where I_{cl} is the thermal resistance of the clothing, [m^{2}K/W]; f_{cl} – the clothing surface area factor; M – metabolic rate, [W/m^2]; W – effective mechanical work, [W/m^2].

In calculation, the mechanical work W was considered, 0, the metabolic rate 69.6 W/m^2 (1.2 met – sedentary work), and the clothing insulation was assumed 0.8 clo (0.124 m^{2}K/W).

The clothing surface factor was calculated using relation (9) [35]:

$$f_{cl} = 1.05 + 0.645 \cdot I_{cl} \tag{9}$$

The clothing temperatures have been determined using the add-in Solver program of Microsoft Excel for all analysed cases with a maximum error of $5.38 \cdot 10^{-8}$.

The average value of the convective heat transfer coefficient was 3.59 W/m^{2}K, the standard deviation (SD) was 0.146, and the average radiant heat transfer coefficient was 3.77 W/m^{2}K (SD = 0.05).

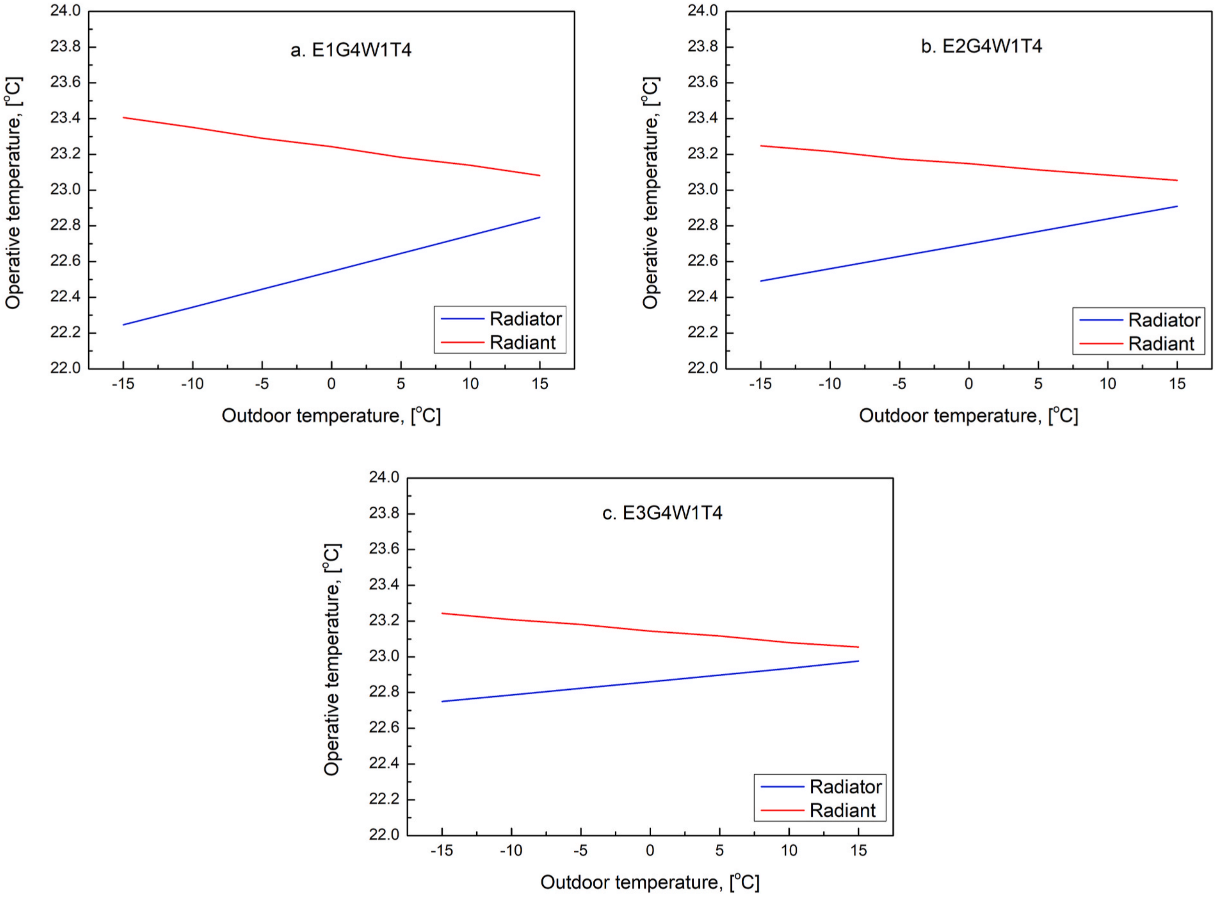

Fig. 5. Operative temperatures in rooms with geometry G4 (4.0m × 4.0m × 2.7m), WWR ratio W1 (20 %) and indoor set-point temperature T4 (23 °C) (a. envelope E1, b. envelope E2, c. envelope E3).

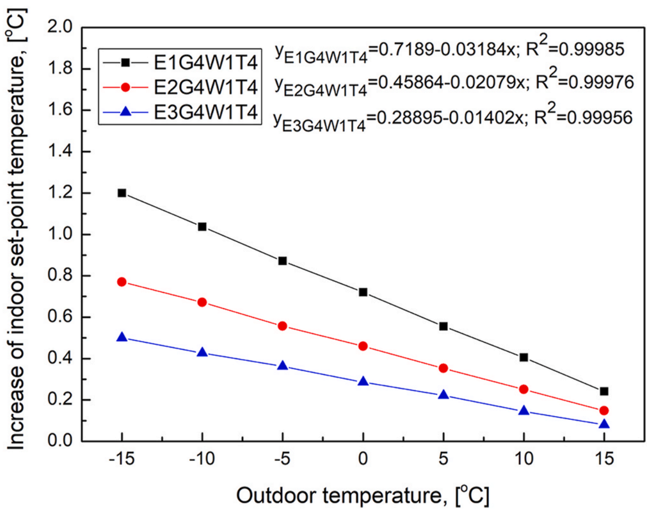

Fig. 6. Increase of the indoor set point temperatures in the case of radiator heating (4.0m × 4.0m × 2.7m, 23 °C and WWR = 20 %).

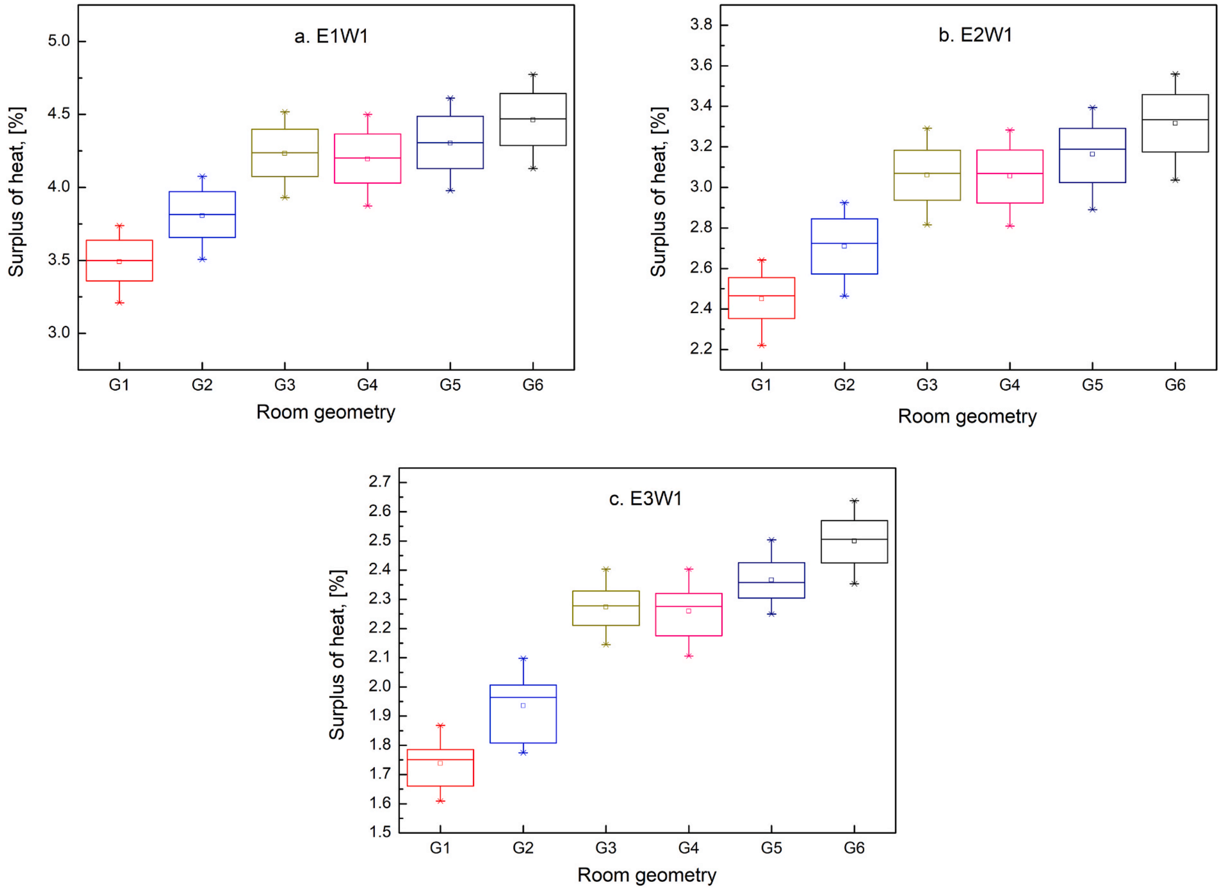

Fig. 7. Surplus of heat depending on geometry (a. E1W1; b. E2W1; c. E3W1), WWR = 20 %.

The mean radiant temperature can be calculated using eq. (10) [36]:

$$\bar{t}_r = \left(\sum F_{P-A_j} \cdot T_j\right)^{0.25} - 273\ [^\circ\mathrm{C}] \tag{10}$$

where F_{P-A_j} is the angle factor between the person and building element j with area A_j; T_j – is the internal surface temperature of building element j, [K].

The operative temperature was determined both for convective heating with a radiator (432 cases) and radiant heating (floor combined with ceiling heating, 432 cases as well).

First, the heat losses were determined for all 432 analysed rooms both for radiator and radiant heating modes. Having the heat loss values at the external design temperature (−15 °C), the heat loss coefficients of the rooms (H) have been calculated. In the case of convective heating mode, the type (22K) and the height of the radiators were set to 600 mm, and the radiators were chosen from the product catalogue [27]. The length of the radiator was chosen to be equal to or almost equal to the width of the window. The logarithmic temperature difference needed to provide the required heat demand was calculated for external design temperature (−15 °C) and, using the heat loss coefficients for −10 °C, −5 °C; 0 °C; +5 °C; +10 °C; +15 °C external temperatures.

2.2.3. Low-temperature radiant heating

The specific heat released by the radiant building element to the room can be determined with relation (11) [16]:

$$\dot{q}_i = h_i \theta_{mi}\ \left[\mathrm{W} / \mathrm{m}^2\right] \tag{11}$$

where θ_{mi} is the mean over-temperature of the radiant building element (the difference between floor and indoor air temperatures, or the difference between ceiling and indoor air temperatures).

The total heat transfer coefficients on the internal surface of the building elements have been chosen based on the study of Shinoda et al. [26]. On the inner floor surface of the floor (floor heating) was assumed $h_i = 11.0\ \mathrm{W/m^2K}$, while on the inner surface of the ceiling (ceiling heating) $h_i = 6.0\ \mathrm{W/m^2K}$.

Using eq. (11), the mean inner surface over-temperature θ_{mi} (the temperature above the indoor air temperature, t_i) of the radiant

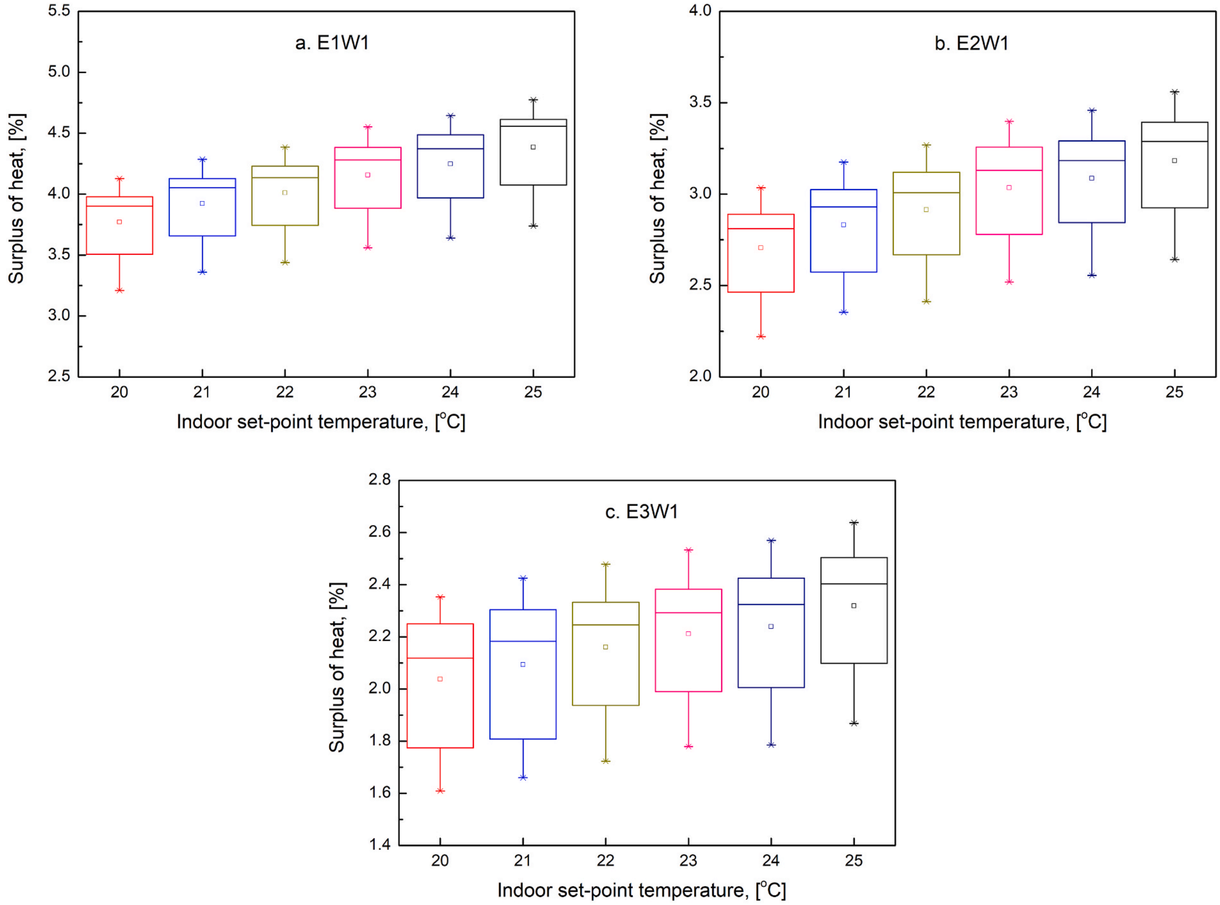

Fig. 8. Surplus of heat depending on indoor air set-point temperature (a. E1W1; b. E2W1; c. E3W1), WWR = 20 %.

building element can be determined.

The mean inner surface over-temperature of the embedded heating layer in the building element will be [37]:

$$\theta_m' = \theta_{mi}\frac{h_i}{\chi_i'}\ [\mathrm{K}] \tag{12}$$

The average over-temperature of the heating fluid (warm water) in the pipes can be determined using the Kollmar relation [37],:

$$\theta_w = \theta_m'\frac{\left(1+h_i\frac{\delta}{\lambda}\right)\frac{ml}{2}}{th\frac{ml}{2}}\ [\mathrm{K}] \tag{13}$$

where: δ is the thickness of the pipes covering layer, [m]; λ – heat conductivity of the heating layer material, [W/mK]; l – distance between the pipes, [m], while the coefficient m is [37]:

$$m = \frac{\chi_i' + \chi_e'}{\delta_{hl}\lambda} \tag{14}$$

where δ_{hl} is the thickness of the heating layer, [m].

The partial heat transfer coefficient of internal layers covering the heating layer (χ_i') can be determined as follows [16]:

$$\chi_i' = \frac{1}{\frac{1}{h_i}+\frac{\delta_p}{\lambda_p}}\ [\mathrm{W/m^2K}] \tag{15}$$

where δ_p – is the thickness of the screed covering the heating layer, [m]; λ_p – is the heat conductivity of the screed covering the heating layer, [W/mK].

The partial heat transfer coefficient of external layers covering the heating layer (χ_e') can be determined using the following equation [16]:

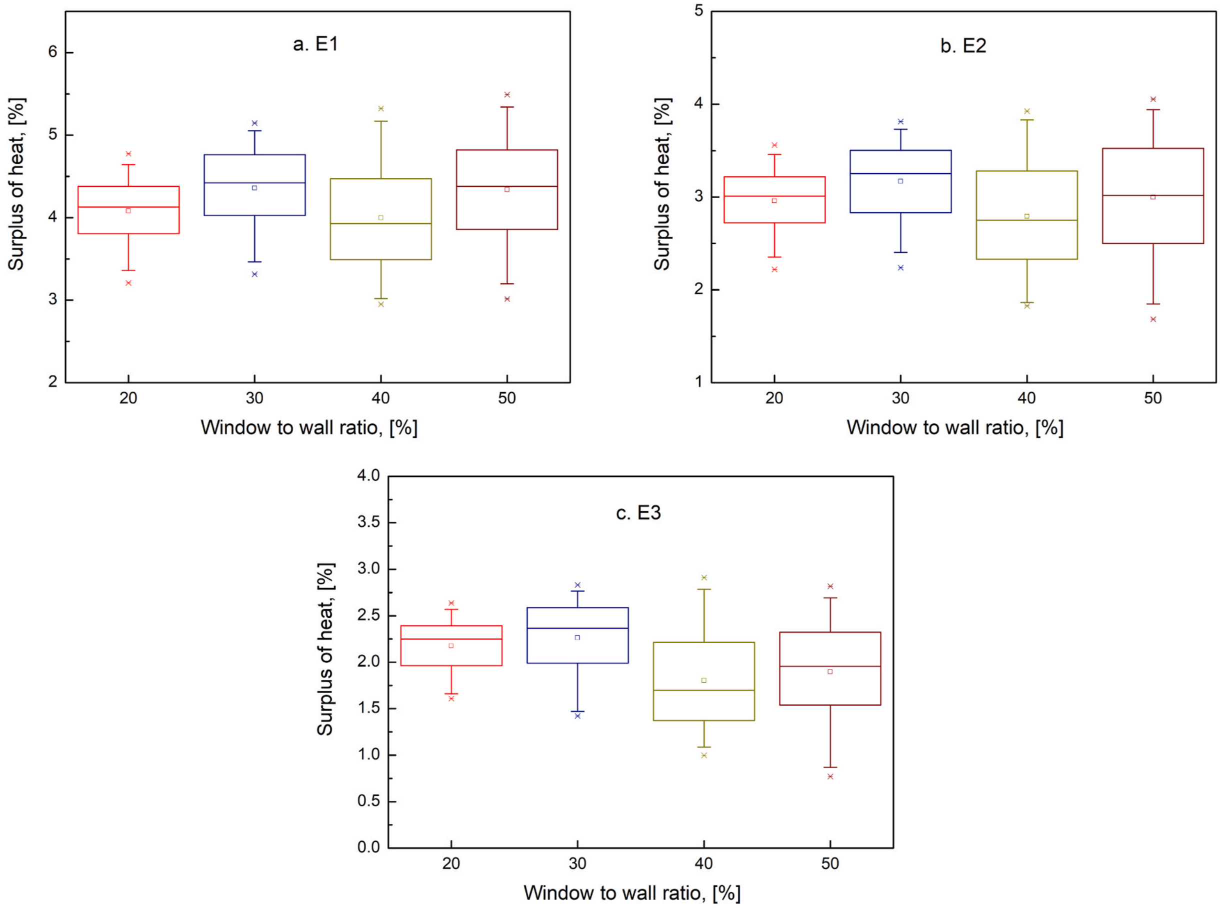

Fig. 9. Surplus of heat depending on WWR (a. E1; b. E2; c. E3).

$$\chi'_e = \frac{1}{\frac{1}{h_e} + \sum_{j=1}^{n} \frac{\delta_j}{\lambda_j}} \ [\mathrm{W/m^2K}] \tag{16}$$

where h_e – is the heat transfer coefficient on the external surface of the building element, [W/m^{2}K]; δ_j – is the thickness of layer j in the building structure situated on the external side of the heating layer, [m]; λ_j – is the heat conductivity of layer j in the building structure situated on the external side of the heating layer, [W/mK].

The specific heat losses can be calculated using eq. (17) [37]:

$$\dot{q}_e = \theta'_m \chi'_e \ [\mathrm{W/m^2}] \tag{17}$$

The calculation methodology was validated by performing measurements in the case of wall heating [16]. A difference of 2.5 % was identified between measured and calculated values. In the case of floor heating, the experimental measurements performed by Shin et al. were used [17]. Fig. 3 shows the heat fluxes depending on the floor temperature, while the results of statistical analysis of the heat flux values are presented in a box plot diagram (Fig. 4).

A pair sample t-test was performed using the ORIGIN LAB 9.55 software to analyse the significance of differences between calculated heat flux values and experimentally measured values [17]. It was found that at a $p = 0.005$ significance level, there is no significant difference between the heat flux values.

In the case of radiant heating, the heat demand was chosen to be covered 60 % by floor heating and 40 % by ceiling heating (taking into account the discomfort that might be caused by a warm ceiling).

The calculations were done using Microsoft Excel tables, subroutines and add-ins. Assuming that a person is in a sitting position in the middle of the room, the angle factors have been determined from diagrams recommended by Fanger [36]. The mean radiant temperatures, the clothing temperatures, and the convective and radiant heat transfer coefficients have been calculated using equations (6)–(10) for all 864 cases (432 cases for radiator heating, 432 cases for radiant heating). Taking into account the assumed external temperatures, the operative temperatures have been determined for 6048 cases.

Besides the temperatures of the heating surfaces (radiator, floor, or ceiling) the internal surface temperatures have been calculated

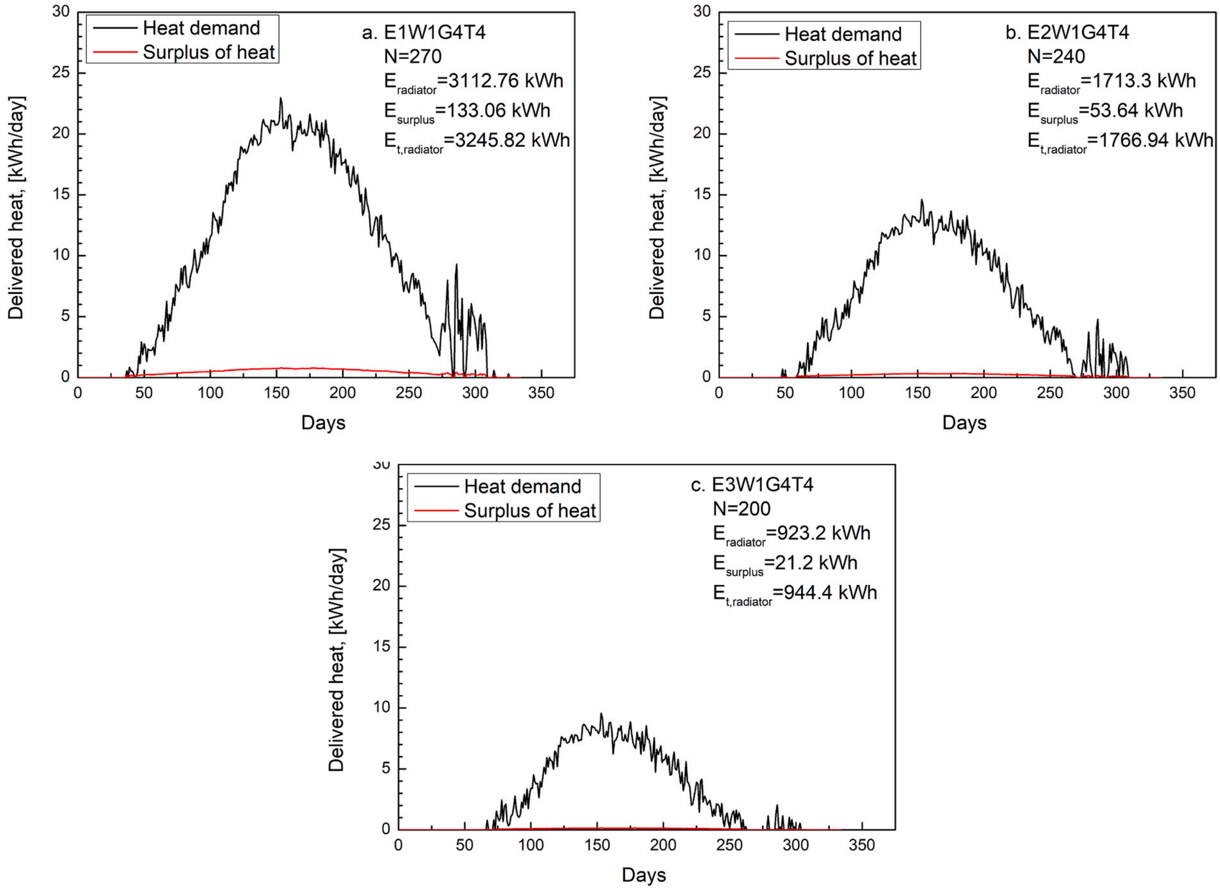

Fig. 10. Energy demand for radiator heating (a. E1W1G4T4; b. E2W1G4T4 c. E3W1G4T4) (23 °C, WWR = 20 %).

for both heating modes. The calculation algorithm and the main equations are presented in Appendix 1.

3. Results and analysis

The variation of the operative temperatures depending on the outdoor temperatures, assuming a certain geometry (G4), windows-to-wall ratio (W1), and a certain temperature (T4), and different building envelopes are presented in Fig. 5.

In the case of radiator heating the operative temperatures are increasing, while the operative temperatures are decreasing at higher outdoor temperatures for radiant heating. At the same time, the better the thermal performance of the building envelope, the higher the operative temperature is in the case of radiant heating. In contrast, in the case of radiator heating the operative temperatures are lower at better thermal performance of the envelope. As a next step, in the case of radiator heating, the increases in indoor set-point temperatures have been determined to obtain the same operative temperatures as in the case of radiant heating (Fig. 6). The increase of the indoor set-point temperatures shows a linear variation depending on the external temperatures for a certain analysed case.

The energy calculations have been performed using equations (1)–(4) assuming the south orientation of the glazed façade (85 % glazing, 15 % frame), solar factor $g = 0.65$. In the case of radiator heating besides the energy used for heating the surplus of heat used to provide higher indoor air temperatures has been determined in all analysed 432 cases. The increases in the energy consumption for a certain WWR, for different envelopes, depending on geometry are presented in Fig. 7. The statistical analysis was done using the values obtained for different indoor air temperatures.

It can be observed that the room geometry has an important effect on the surplus of heat demand. The increases in the energy consumption for a certain WWR, for different envelopes depending on indoor air set-point temperatures are presented in Fig. 8. The statistical analysis was done using the values obtained for different geometries.

It can be observed that an increase of 1K will not lead to a significant increase in the surplus of heat. The surplus of heat depending on the WWR is presented in Fig. 9. The statistical analysis was done using the values determined for all indoor air temperatures and all geometries for a certain WWR.

The delivered heat in the case of radiator and radiant heating are presented in Figs. 10 and 11. The daily mean outdoor temperature values have been determined from the 1st of August to the 30th of June next year based on meteorological data provided by the Hungarian Meteorological Service for Debrecen (1990–2020) [38]. The daily mean solar energy yield on vertical surfaces was

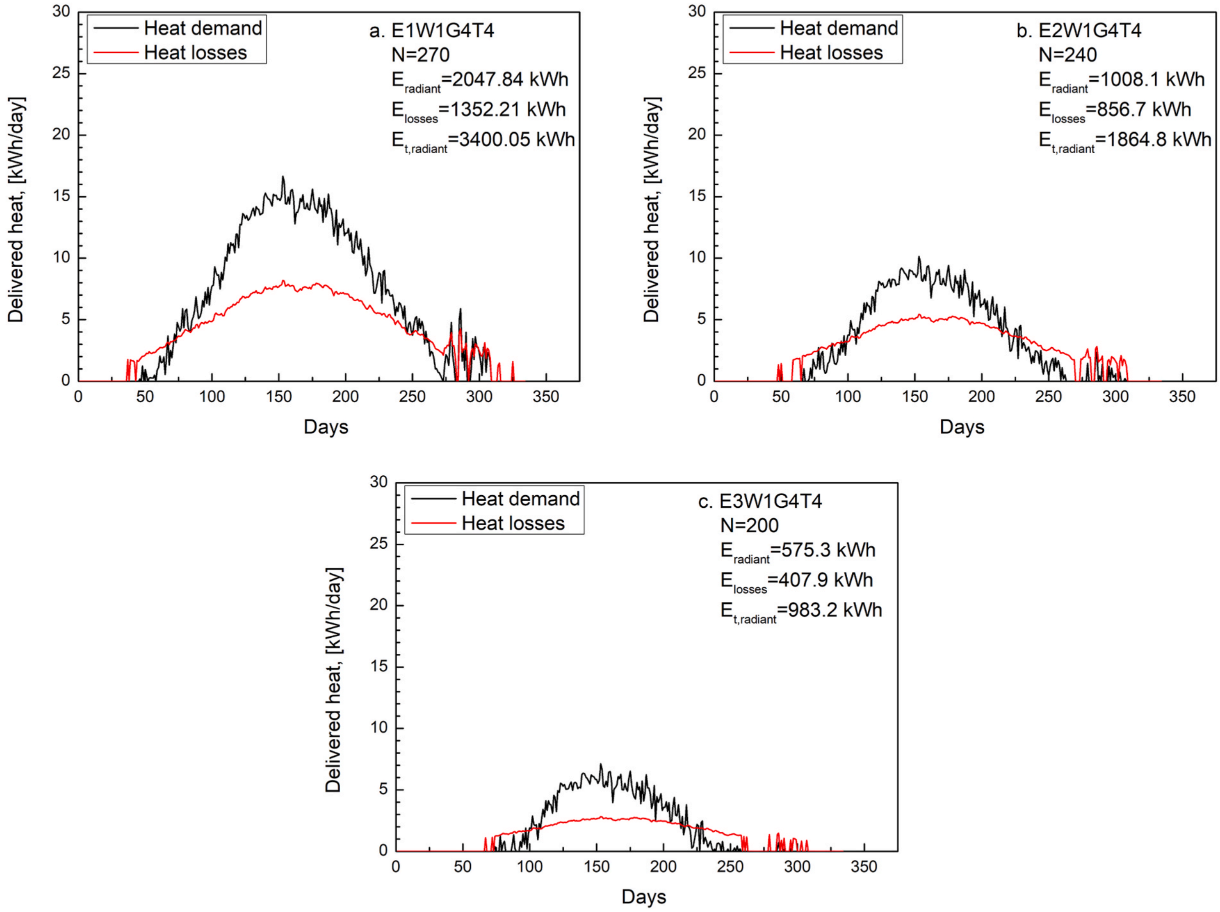

Fig. 11. Energy demand for radiant heating (a. E1W1G4T4; b. E2W1G4T4 c. E3W1G4T4) (23 °C, WWR = 20 %).

calculated using the hourly global solar radiation data provided by Meteorological Observatory, University Debrecen (Hungary) [16].

Having the total energy demand for heating for both radiator ($E_{t,radiator}$) and radiant heating ($E_{t,radiant}$), the differences in percentage (e_{diff}) have been determined for the analysed 432 cases (in a certain case the difference was reported always to the higher energy demand).

The differences between energy consumptions for a certain WWR, for different envelopes, depending on geometry are presented in Fig. 12. The statistical analysis was done using the values obtained for different indoor air temperatures.

The energy demand for heating is higher for low-temperature radiant heating in all analysed cases, and the differences between energy demands are increasing in the case of larger rooms. However, this increase depends on the thermal performance of the building envelope. It can be stated that the highest differences have been obtained for envelope type E2. To see the effect of geometry on the differences between energy demands, one-way ANOVA analysis was performed for presented situations (Tukey test).

The homogeneity variance was tested using Levene's method. In the case of envelopes E1 and E2 at a $p = 0.05$ significance level, the differences between means and variances are not significant. However, in the case of the E3 envelope, at $p = 0.05$ level, the differences between variances are not significant, while the differences between the means are significant between geometries: G1-G4, G1-G5, G1-G6, and G3-G6. The differences between variances are not significantly different, but the differences between means are significantly different between cases E1-E2, E1-E3, and E2-E3 for all analysed geometries except G4. Furthermore, the differences between the energy consumptions for a certain WWR and for different envelopes depending on indoor air set-point temperatures are presented in Fig. 13. The statistical analysis was done using the values obtained for different geometries.

It was found that at higher indoor air temperatures, radiant heating shows higher energy needs than radiator heating. The highest differences between radiant and radiator heating have been obtained for envelope E2. Performing the one-way ANOVA significance analysis at $p = 0.05$ significance level, it was obtained that for envelope E1 the differences between the means are significant between all cases except 22 °C–23 °C, 23 °C–24 °C, and 24 °C–25 °C. For envelope E2 the differences between means are not significant between 20 °C–21 °C, 21 °C–22 °C, 22 °C–23 °C, 22 °C–24 °C, 23 °C–24 °C, 23 °C–25 °C, and 24 °C–25 °C. In the case of envelope E3 the differences between means are significant between 20 °C–24 °C and 20 °C–25 °C indoor air set point temperatures.

The significance analysis was performed for each indoor set-point air temperature depending on the envelope type. It was found that there are no significant differences between the means and variances for 20 °C and 21 °C air set-point temperatures. The

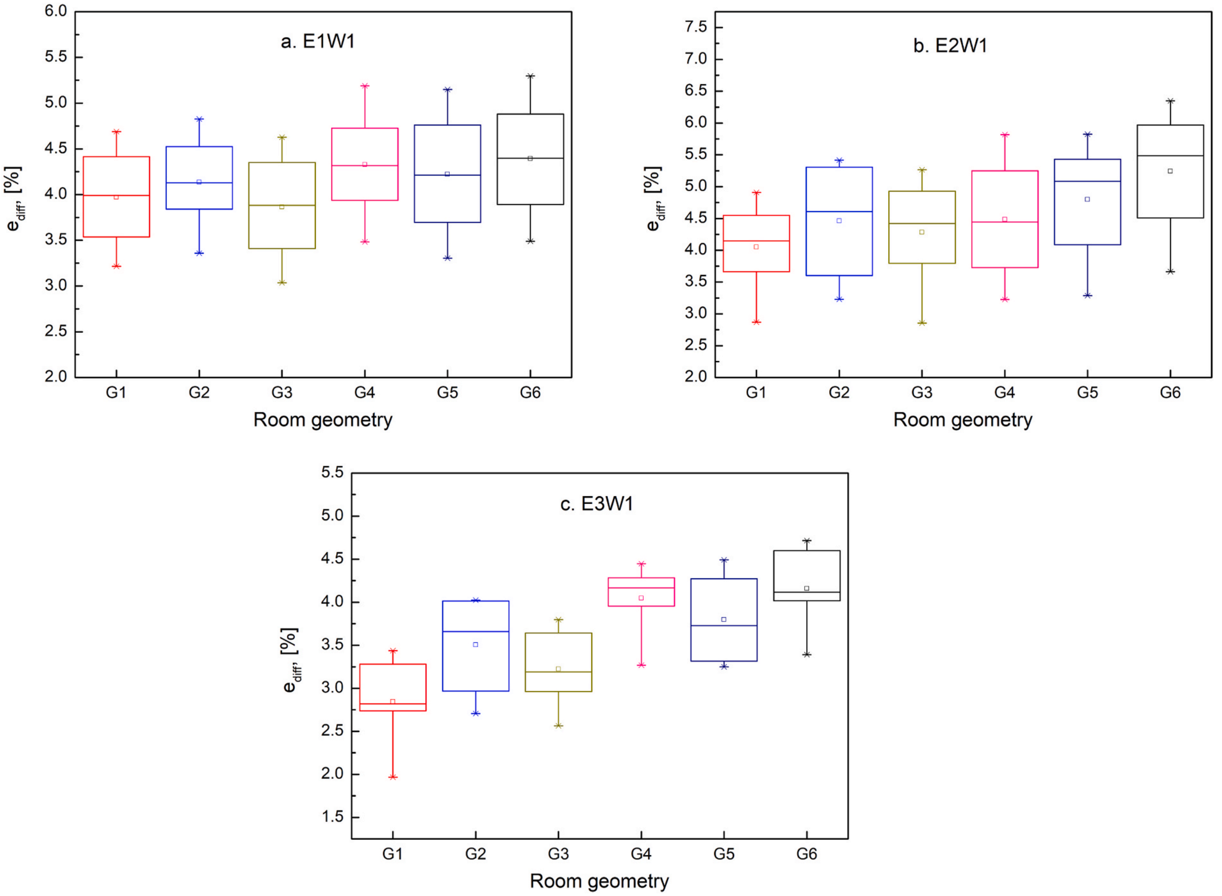

Fig. 12. Differences between the energy demand for radiant and radiator heating depending on geometry (a. E1W1; b. E2W1; c. E3W1), W1 = 20 %.

differences are significant between E2-E3 for 22 °C and 23 °C. Furthermore, significant differences have been found between E1-E3 and E2-E3 in the case of 25 °C, while the differences were significant between all envelopes for 24 °C.

The differences between the energy consumption depending on the WWR are presented in Fig. 14. The statistical analysis was done using the values determined for all indoor air set-point temperatures and all geometries for a certain WWR.

Performing the one-way ANOVA analysis for the E1 at $p = 0.05$ significance level envelope it was found that the differences are significant between 20% and 40 %, 20%–50 %, 30%–40 %, and 30%–50 % windows-to-wall ratios. For the E2 envelope, the differences are significant between all analysed WWR cases except 40%–50 %. In the case of the E3 envelope type the significance test revealed that the differences between the means are not significant except in the case 20%–40 %.

4. Discussion

Several scholars have stated that low-temperature radiant heating systems provide better comfort than convective heating systems [9,12,13]. Lin et al. in their study, found that in continuous heating, no significant difference between radiant and convective heating systems was observed in the mean radiant temperature [39]. In this study, it was shown that the operative temperature assured by low-temperature radiant heating is higher than the operative temperature obtained in the case of radiator heating. A higher operative temperature in the heating season results in better thermal comfort.

However, the differences between the operative temperatures are not constant during the heating season but decrease at higher outdoor temperatures because the operative temperature provided by radiant heating decreases, while the operative temperature provided by radiator heating increases at higher outdoor temperatures. The increase of the operative temperature in the case of radiator heating can be obtained by increasing the air temperature. The increase in the air temperature is obtained by increasing the radiator temperature. In this case, practically all indoor surface temperatures will increase, and the higher operative temperature is obtained by a parallel and interdependent increase of the air and mean radiant temperatures (for more information see Appendix 3, subsection A3.1). Thus, the higher operative temperature is obtained by increasing the energy used for heating.

As shown in the results, the surplus of heat depends on a series of factors: room geometry, thermal properties of the envelope, windows-to-wall ratios, and indoor set point temperatures. Analysing 432 different cases, it was obtained that the provided heat has to be increased on average by 3.07 % (SD = 1.03) (see Fig. A2.1, Appendix 2). Adding the calculated surplus of heat to the energy

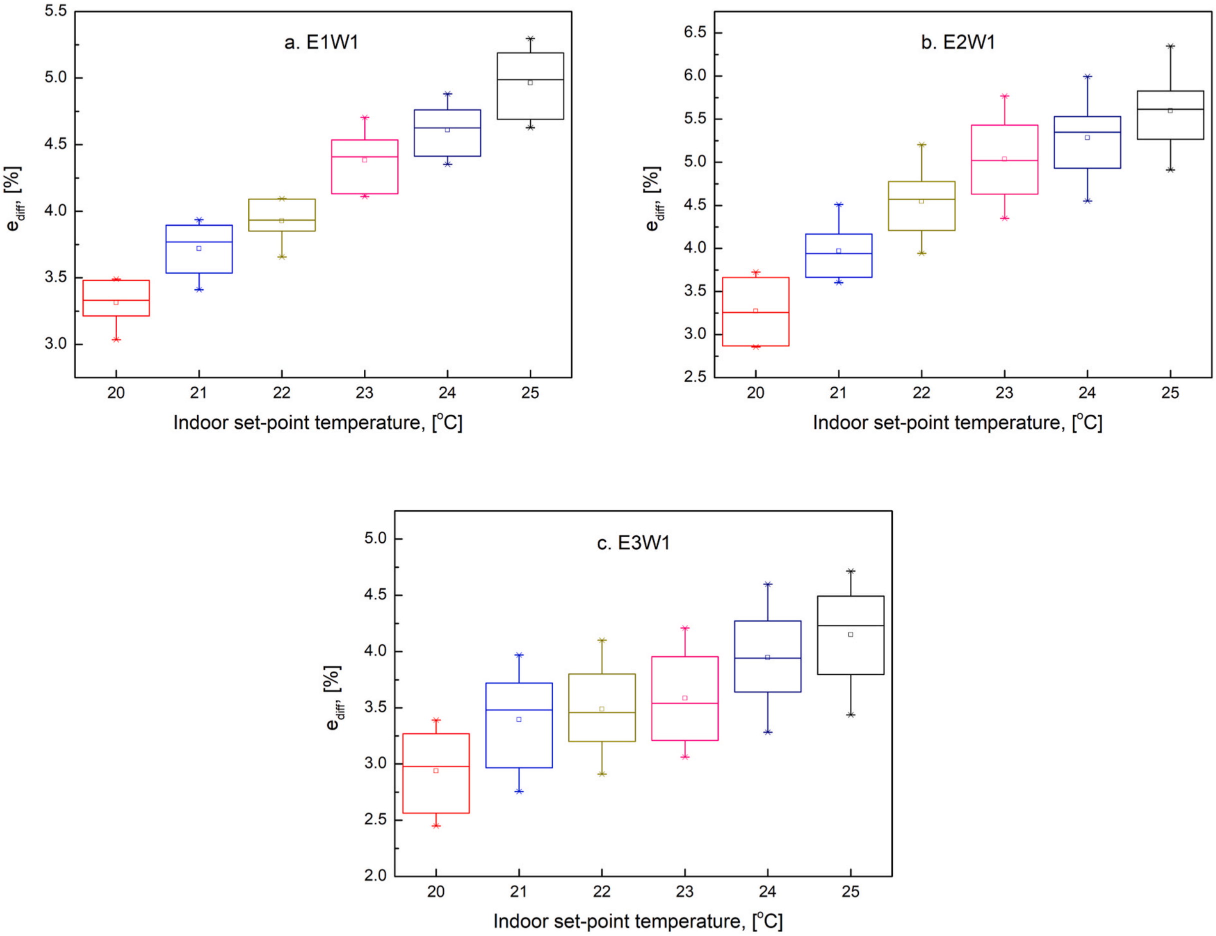

Fig. 13. Differences between the energy demand for radiant and radiator heating depending on indoor air set-point temperature (a. E1W1; b. E2W1; c. E3W1), W1 = 20 %.

demand, the total energy demand for heating in the case of radiator heating is obtained which will assure the same operative temperature as the low-temperature radiant heating (ceiling combined with floor heating in this case).

It was shown that the energy provided in the heated room in the case of low-temperature radiant heating is lower than in the radiator heating case. However, in the case of heating layers embedded in external building elements substantial heat losses accompany the heating process [16]. For the analysed 432 cases, the average value of the total heat losses of low-temperature radiant heating (floor and ceiling) is 40.71 % (SD = 5.3) (see Fig. A2.2, Appendix 2). The obtained heat losses agree well with the results published by Li et al. [15]. These heat losses have to be taken into account when the radiator and the low-temperature radiant heating systems are compared. Therefore, in this case, the total energy demand for heating is obtained by adding to the heat delivered in the room the heat losses of the system.

It has to be taken into account that in the case of embedded heating layers the heating season length is similar to the radiator heating mode, but a certain number of days is enough to provide a surface temperature equal to the indoor set-point temperature. In this way, the heat demand will decrease and the heat gains of the room will cover the heat losses for a longer period. Practically, the embedded heating layer is operating as a thermal barrier in this period. For the analysed 432 cases the "thermal barrier" operation mode lasts between 8 and 56 days (see Fig. A2.3, Appendix 2). The longest period for the "thermal barrier" operation mode was obtained for larger rooms and better thermal performances of the envelope (for more information see Appendix 3, subsection A3.2).

For the analysed heating season, the mean surface temperatures needed are 24.7 °C (floor) and 25.07 °C (ceiling) (see Fig. A2.4, Appendix 2)). It can be observed that despite the 60%–40 % shares of heat demand for floor and ceiling respectively, the ceiling temperature slightly exceeds the floor temperature because of the lower surface heat transfer coefficient. The obtained ceiling temperature is high, but acceptable from a thermal comfort point of view, taking into account the height of the investigated rooms). Safizadeh et al. carried out measurements and studied the thermal comfort in the case of higher ceiling temperatures (28 °C, 33 °C, and 38 °C) [19]. The average supply/return temperature for radiator heating in the case of −15 °C outdoor temperature is 55.33 °C–35.33 °C (SD = 7.1, min: 43.04 °C–23.04 °C; max: 78.47 °C–58.47 °C) (see Fig. A2.5, Appendix 2).

Comparing at equal operative temperatures the total energy demand for heating in the case of the radiator and low-radiant heating

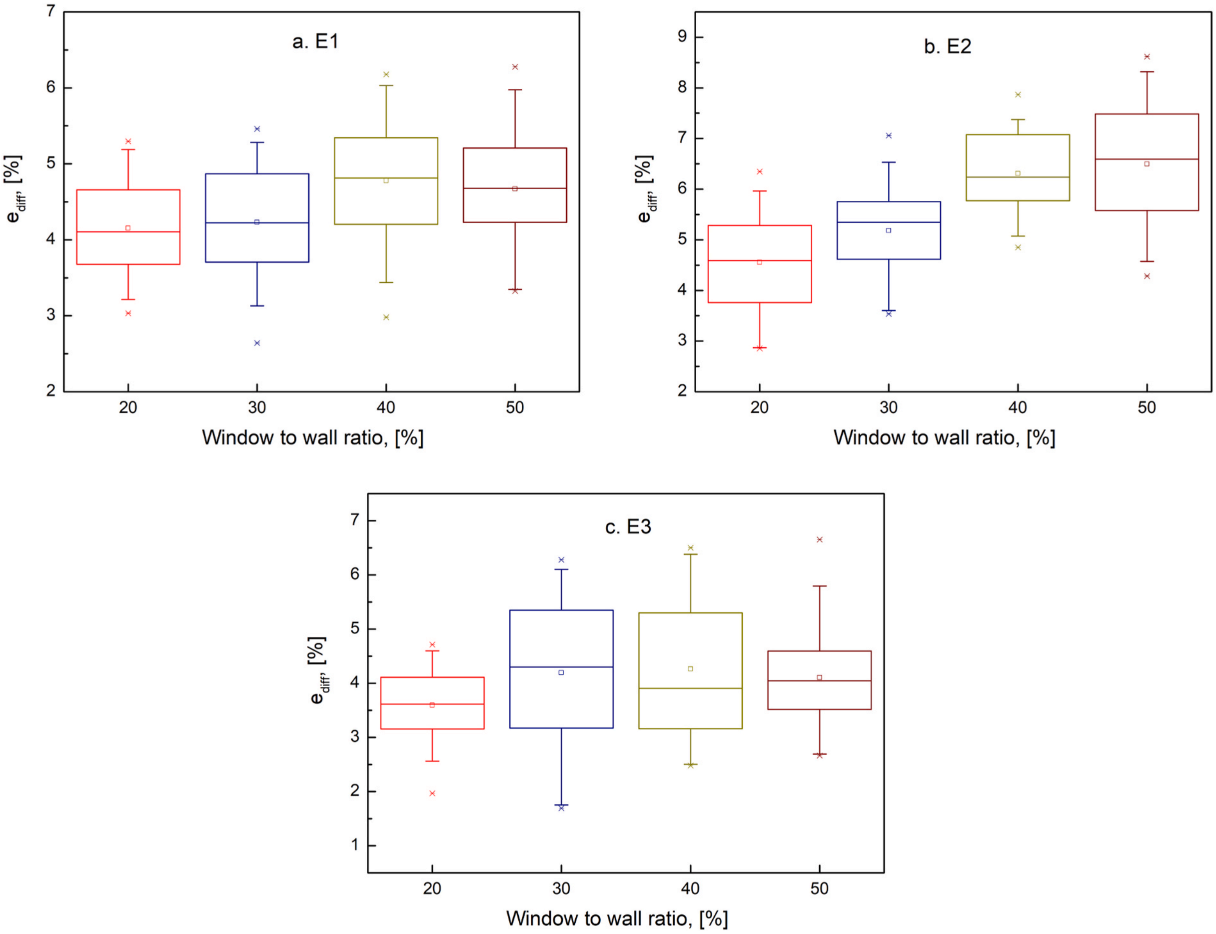

Fig. 14. Differences between the energy demand for radiant and radiator heating depending on WWR (a. E1; b. E2; c. E3).

systems for all investigated 432 cases, it can be stated that in all cases the radiant heating system needs more energy for heating than the radiator heating system. The energy demand of radiant heating mode (combined floor and ceiling) exceeds the radiator heating mode on average by 4.71 % (SD = 1.25) (see Fig. A2.6, Appendix 2). The average value of heat released in the room is 1577.7 kWh (SD = 1031.8) in the case of radiator heating and 998.8 kWh (SD = 647.4) in the case of combined floor and ceiling radiant heating (see Fig. A2.7 and A2.9, Appendix 2). However, the average surplus of heat in the case of radiator heating at equal operative temperature is 57.8 kWh (SD = 53.6) (Fig. A2.8, Appendix 2), while the average heat loss in the case of radiant heating is 721.3 kWh (SD = 509.7) (see Fig. A2.9, Appendix 2).

5. Conclusions

This research investigated, calculated, analysed, and compared heating energy demands between low-temperature radiant heating and radiator heating. It is shown that at an equal set-point indoor air temperature, better thermal comfort is provided because of higher operative temperatures using radiant heating. In the case of radiator heating, increasing the supply/return temperatures higher indoor air and higher mean radiant temperatures are obtained but the energy demand for heating will increase as well. The operative temperatures in the case of low-temperature radiant heating decrease to a small extent at higher outdoor temperatures, while the operative temperatures increase to a small extent at higher outdoor temperatures in the case of radiator heating. This means that the surplus of heat used in the case of radiator heating to provide similar operative temperatures as the low-temperature radiant heating provides decreases at higher outdoor temperatures. Nevertheless, in the case of low-temperature heating systems with embedded circuits, the heat losses of the system must be taken into account to see the overall efficiency of the heating system.

By performing significance analysis, it was revealed that the different combinations of the room geometry, indoor set point temperature, and windows-to-wall ratio can lead to significant disparities between the total energies needed for heating in the case of the radiator and the radiant heating.

It has to be mentioned that in the case of low-temperature radiant heating systems lower operating temperatures (supply and return) are needed in comparison to radiator heating. The seasonal energy efficiencies of the heat sources (condensing boiler or heat pump) ought to be determined for the whole heating season to investigate the effects on the energy consumption of supply/return temperature differences between the analysed heating system types.

The heat losses of low-temperature radiant heating systems can be avoided or reduced substantially and the advantages of these heating systems can be efficiently harnessed in multilevel buildings embedding the heating layers in internal building elements (slabs between the floors, or internal walls).

Further research: The energy analysis ought to be continued analysing energy consumption at the heat source. The energy comparison of radiator and radiant heating systems has to be done in the case of multilevel buildings as well. The research should be done by comparing the energy demand for heating in countries with different climates.

5.1. Limitations

This study was performed on 432 room models. By increasing the number of models, more general conclusions could be obtained. The energy analysis was done taking into account the average outdoor temperatures registered in Debrecen (Hungary) in the last 30 years. The calculation methodology is robust and can be used in any other climate. Using other climate parameters the differences between energy consumption may differ from those obtained in this study.

CRediT authorship contribution statement

Tünde Kalmár: Writing – original draft, Validation, Investigation, Formal analysis, Data curation. **Béla Bodó:** Visualization, Investigation, Data curation. **Shiyu Han:** Writing – review & editing. **Baizhan Li:** Writing – review & editing. **Ferenc Kalmár:** Writing – review & editing, Methodology, Conceptualization.

Declaration of Generative AI and AI-assisted technologies in the writing process

The authors declare that no AI or AI-assisted technologies were used in the writing process.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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List of abbreviations and symbols

NZEB	– nearly zero energy buildings
DHW	– domestic hot water
G1	–2.0m × 3.0m × 2.7m room geometry
G2	–3.0m × 3.0m × 2.7m room geometry
G3	–3.0m × 4.0m × 2.7m room geometry
G4	–4.0m × 4.0m × 2.7m room geometry
G5	–4.0m × 5.0m × 2.7m room geometry
G6	–5.0m × 5.0m × 2.7m room geometry
WWR	– windows-to-wall ratio
W1	– WWR = 20 %
W2	– WWR = 30 %
W3	– WWR = 40 %
W4	– WWR = 50 %
T1	– $t_i = 20$ °C
T2	– $t_i = 21$ °C
T3	– $t_i = 22$ °C
T4	– $t_i = 23$ °C
T5	– $t_i = 24$ °C
T6	– $t_i = 25$ °C
E1	– envelope type 1 (see Table 1)
E2	– envelope type 2 (see Table 1)

E3 – envelope type 3 (see Table 1)
ACH – air change rate, [1/h]
Eh – energy demand for heating, [kWh]
N – the number of heating days
H – heat loss coefficient of the room, [W/K]
t_i – indoor set point temperature, [°C]
t_e – mean outdoor temperature of heating day j, [°C]
$\dot{Q}_i$ – mean value of indoor heat gains in a heating day, [W]
$\dot{Q}_{sj}$ – mean value of solar heat gains in the j heating day, [W]
C – heat storage capacity, [J/K]
τ – room time constant, [h]
η_H – utilization factor of heat gains, [−]
γ_H – the ratio between daily heat gains and heat losses of the room, [−]
k – correlation coefficient, [−]
D – correlation coefficient, [−]
t_o – operative temperature, [°C]
$\bar{t}_r$ – mean radiant temperature, [°C]
h_c – convective heat transfer coefficient of the human body, [W/m^{2}K]
h_r – radiant heat transfer coefficient of the human body, [W/m^{2}K]
t_{cl} – clothing temperature, [°C]
A_r – effective radiant surface of the human body, [m^2]
A_{Du} – Du Bois surface of the human body, [m^2]
ε – emission coefficient of clothing surface and human body uncovered by clothing, [−]
I_{cl} – thermal resistance of the clothing, [m^{2}K/W]
f_{cl} – clothing surface area factor
M – metabolic rate, [W/m^2]
W – effective mechanical work, [W/m^2]
SD – standard deviation, [−]
F_{P-A_j} – angle factor between the person and building element j with area A_j, [−]
T_j – internal surface temperature of building element j, [K]
$\dot{q}_i$ – specific heat released by the radiant building element to the room, [W/m^2]
$\dot{q}_e$ – specific heat losses of the radiant building element, [W/m^2]
h_i – total heat transfer coefficients on the internal surface, [W/m^{2}K]
h_e – total heat transfer coefficients on the external surface, [W/m^{2}K]
θ_{mi} – mean inner surface over-temperature of the radiant building element, [K]
θ_m' – mean inner surface over-temperature of the embedded heating layer, [K]
θ_w – average over-temperature of the heating fluid, [K]
δ – thickness of the pipes covering layer, [m]
λ – heat conductivity of the heating layer material, [W/mK]
l – distance between the pipes, [m]
m – coefficient, [−]
δ_{hl} – thickness of the heating layer, [m]
χ_i' – partial heat transfer coefficient of internal layers covering the heating layer, [W/m^{2}K]
χ_e' – partial heat transfer coefficient of external layers covering the heating layer, [W/m^{2}K]
δ_p – thickness of the screed covering the heating layer, [m]
λ_p – heat conductivity of the screed covering the heating layer, [W/mK]
δ_j – thickness of layer j in the building structure situated on the external side of the heating layer, [m]
λ_j – is the heat conductivity of layer j in the building structure situated on the external side of the heating layer, [W/mK]
p – significance level, [−]
$E_{t,radiator}$ – total energy demand for heating in the case of radiator heating system, [kWh]
$E_{t,radiant}$ – total energy demand for heating in the case of radiant heating system, [kWh]
e_{diff} – the difference between the total energy demand for heating in the case of analysed heating systems, [%]

Appendix 1

Calculation algorithm and equations

The steps of the calculation algorithm are.

1 Heat losses have been determined for all 432 cases both for radiator and radiant heating.
2 The heat loss coefficients of the analysed rooms were determined by dividing the heat losses by the temperature differences (indoor set point temperature and external design temperature).
3 Using the heat loss coefficients of the rooms the heat losses have been calculated for different outdoor temperatures: −10 °C; −5 °C; 0 °C; +5 °C; +10 °C; +15 °C.
4 Having the heat losses of the rooms and the available heating surface (both for radiator and radiant heating mode) the surface temperatures of the heating elements were determined (the heat released was assumed to be equal to the heat loss of the room). A qualitative control of the heating system was considered (the mass flow of warm water is constant during the heating season, and the heating capacity is controlled by adjusting the supply and return temperatures of the warm water).
5 Surface temperatures of all building elements were determined for all rooms and all outdoor temperatures.
6 Angle factors have been determined considering a sitting person in the middle of the rooms.
7 Mean radiant temperatures were determined for all 432 + 432 room models.
7 Clothing temperature was determined in each case.
8 Operative temperature was calculated for all room models at different outdoor temperatures.
7 The differences between the operative temperatures (radiant heating mode and radiator heating mode) were determined.
8 It was observed that these differences are linear. The functions describing the operative temperature differences depending on the outdoor temperature were determined using ORIGIN LAB software.
9 Using the hourly outdoor temperature and solar radiation data (1990–2020) the daily mean values were determined.
10 For 334 days (1st August-30th of June next year) the daily heat losses and heat gains have been determined for all 432 cases.
11 Using the Yohannis-Norton equations, the utilization factor of heat gains was determined for each day in all 432 cases.
12 The energy needed for heating in the case of radiant heating was calculated for each heating day for all analysed room models.
12 Assuming the same operative temperature for radiator heating as it was obtained for radiant heating, using the SOLVER add-in program of Microsoft Excel the new air, radiator and surface temperatures were determined in the case of radiator heating.
13 Having the new temperature values, the increased energy consumption was determined for radiator heating.
14 The surplus of heat was calculated in the case of radiator heating which must be provided to obtain a similar operative temperature as it was obtained in the case of radiant heating.
15 The heat losses of radiant heating were calculated for all 432 cases.
16 The differences between the energy consumption for heating were determined in the case of radiant and radiator heating.

A1.1. Heat losses

The heat losses of the room are the sum of transmission and ventilation heat losses. The transmission heat losses are:

$$\dot{Q}_{tr} = H_{tr}(t_i - t_e) = \left(\sum A \cdot U \cdot C + \sum \Psi \cdot l\right)(t_i - t_e) \tag{A1}$$

where: $\dot{Q}_{tr}$–transmission heat losses, [W]; H_{tr}–transmission heat loss coefficient, [W/K]; A –surface of an external building element, [m2]; U – overall heat transfer coefficient of the external building element, [W/m2K]; C – temperature correction factor:

$$C = \frac{t_i - \widehat{t}_e}{t_i - t_e} \tag{A2}$$

where i $\widehat{t}_e$ s the temperature on the cold side of the external building element, [°C]. This can be different than te in the case of an unheated cellar or unheated attic.

The ventilation heat losses are:

$$\dot{Q}_v = H_v(t_i - t_e) = c \cdot \dot{m} \cdot (t_i - t_e) \tag{A3}$$

where: $\dot{Q}_v$ ventilation heat losses, [W]; –H_v ventilation heat loss coefficient, [W/K]; c – specific heat of the fresh air introduced in the room, [J/kgK]; –$\dot{m}$ mass flow of the fresh air introduced in the room, [kg/s];

$$\dot{m} = \varrho \cdot \dot{V} = \frac{\varrho \cdot ACH \cdot V}{3600} \tag{A4}$$

where: ϱ density of the fresh air, [kg/m3]; – $\dot{V}$ fresh air flow rate, [m3/s]; ACH – the air change rate, [1/h].

The heat loss of the room $\dot{Q}_{room}$ will be:

$$\dot{Q}_{room} = \dot{Q}_{tr} + \dot{Q}_v \tag{A5}$$

In the case of radiant heating, the heat losses must be recalculated because through the radiant surfaces (floor and ceiling) there are no heat losses during the operation of the heating system. The balance point temperature of the room is the same as the balance point temperature calculated for radiator heating, but there are a few days at the beginning and the end of the heating season when it is enough to keep the heating surface equal to the indoor set point temperature (the radiant heating operates in those days like a heat barrier).

A1.2. Radiator heating

The radiators have been chosen the type (22K) and the height of the radiators were set to 600 mm, and the radiators were chosen from the product catalogue. The length of the radiator was chosen to be equal to or almost equal to the width of the window (for more information see Appendix 3, subsection A3.3). The heat released by the radiator for 90 °C supply temperature, 70 °C return temperature and 20 °C indoor set-point temperature are given by the manufacturer in the product catalogue. For any other temperatures, the heat released can be calculated using the equation:

$$\dot{Q} = \dot{Q}_0 \left(\frac{\Delta t}{\Delta t_0}\right)^n \tag{A6}$$

where

$$\Delta t = \frac{t_s - t_r}{ln\frac{t_s - t_i}{t_r - t_i}} \tag{A7}$$

where: ts – heating supply temperature, [°C]; tr – heating return temperature, [°C].

The heat released by the radiator is equal to the heat demand of the room. Thus, the required logarithmic temperature and the supply and return temperatures can be determined.

A1.3. Surface temperatures

Assuming heated neighbour spaces with the same indoor set point temperatures as the analysed rooms, the surface temperatures of internal building elements were considered equal to the indoor set point temperatures. In the case of radiant heating the floor and ceiling temperatures result from the heat demand of the room (60 % heat released by the floor, 40 % heat released by the ceiling). The radiator temperature was considered as the average of supply and return temperatures. The inner surface temperature of external building elements, t_{si}:

$$t_{si} = t_i - (t_i - t_e)\frac{U}{h_i} \tag{A8}$$

where: hi – is the surface heat transfer coefficient on the inner side of the building element, [W/m2^{K}].

Appendix 2

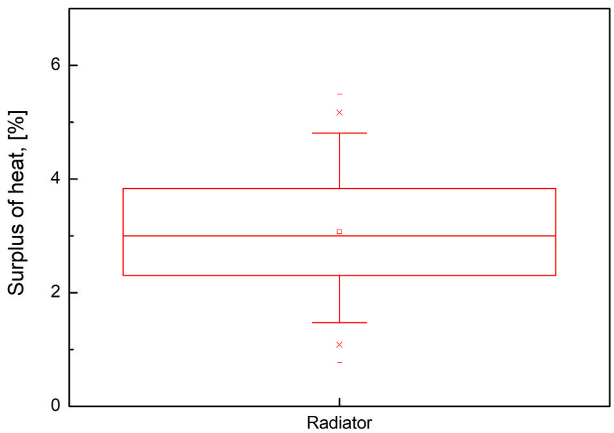

Fig. A2.1. Surplus of heat needed for radiator heating.

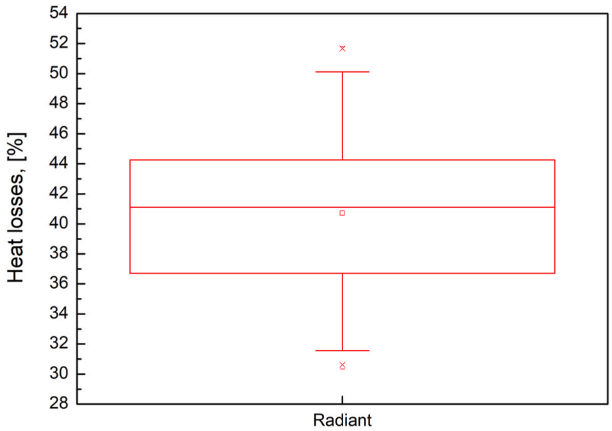

Fig. A2.2. Heat losses of radiant heating system.

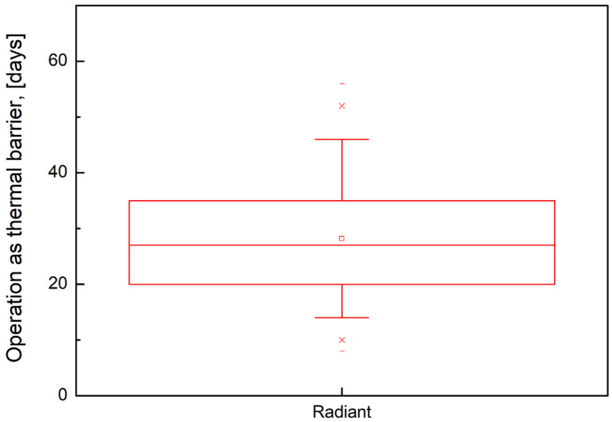

Fig. A2.3. Operation time of radiant heating as a thermal barrier.

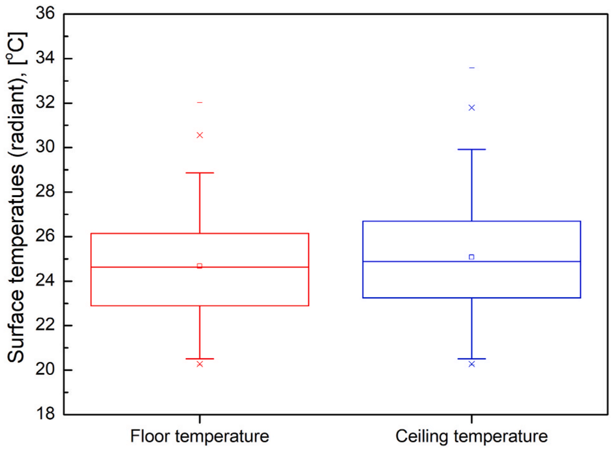

Fig. A2.4. Surface temperatures (radiant heating).

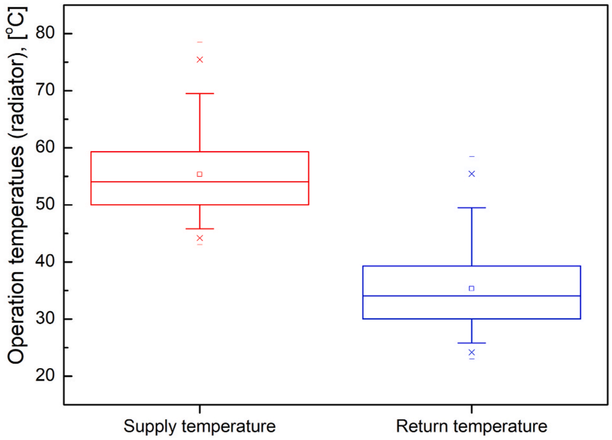

Fig. A2.5. Operation temperatures (radiator heating).

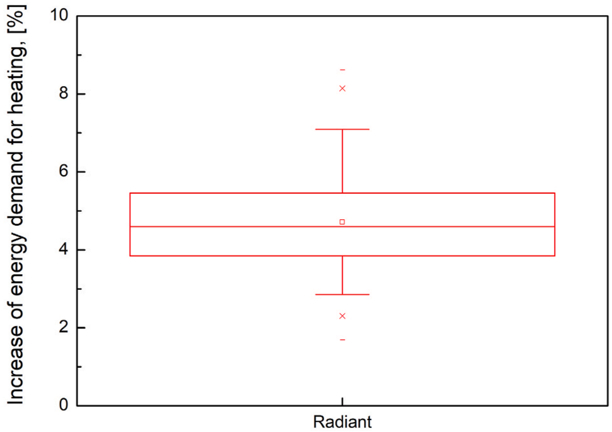

Fig. A2.6. Increase of heat demand in the case of radiant heating (in comparison to radiator heating).

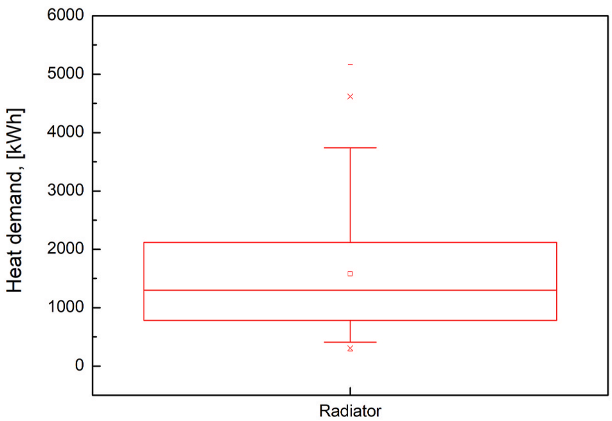

Fig. A2.7. Heat demand in the case of radiator heating.

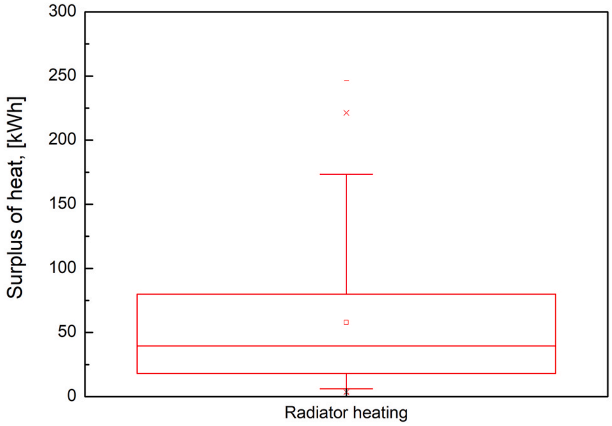

Fig. A2.8. Surplus of heat needed in the case of radiator heating.

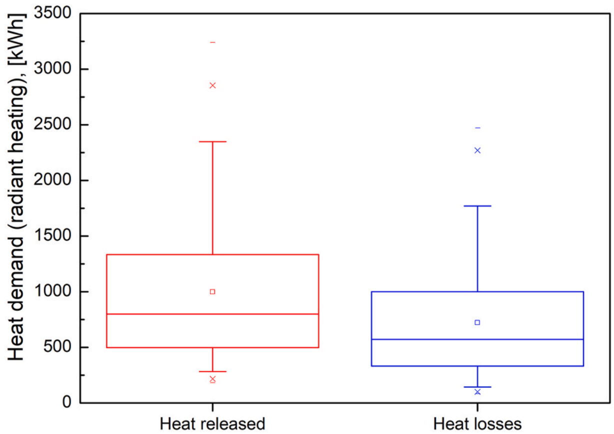

Fig. A2.9. Heat demand in the case of radiant heating.

Appendix 3

Supplement to the Discussion chapter

A3.1. The heating surfaces both in the case of the radiator and radiant heating are given (in the case of ceiling and floor these are the net floor area and ceiling area, in the case of radiator heating the height is 600 mm, the length is equal to the window width). The design supply and return temperatures were calculated depending on the room's heat demand (determined at −15 °C). In the case of higher outdoor temperatures, the inner surface temperatures of the external building elements will increase, but the surface temperature of the heating surfaces will decrease (because of lower heat demands). The operative temperature is calculated depending on the indoor air temperature and mean radiant temperature ($\bar{t}_r$). $\bar{t}_r$ is calculated using eq. (10). In this equation the angle factors have an important role. The radiator's angle factor is small compared to the angle factors of the ceiling and floor. The decrease in the ceiling and floor temperatures will have a higher weight in the $\bar{t}_r$ value than the decrease in the radiator temperatures (where the increase in the building surfaces' inner temperature will have a higher weight). That's why at higher outdoor temperatures the operative temperatures increased in the case of radiator heating and decreased in the case of radiant heating.

A3.2. The energy needed for heating was calculated considering all heating days in a year. The outdoor temperatures and solar radiations for the year considered in the calculations were determined based on the meteorological data collected by the Hungarian Meteorological Service and the University of Debrecen. According to this data, there are several heating days in May, June, August and September. The heat demand of the analysed rooms on these days is not too high and in reality, the heating systems are not switched on for one or two days in August if the indoor air temperature is lower by 0.2 or 0.5 °C than the set-point value. Nevertheless, the calculation was done to identify all those days when the indoor temperature is below the set-point temperature as heating days. In the case of simplified degree-day calculations, the balance point temperature of a room or building represents the limit of the heating season. This is a consequence of the fact that the daily mean outdoor temperatures are presented in the degree-day curve in ascending order. When the daily mean outdoor temperatures are presented for a longer period (a month or some months) day by day, the delimitation of the heating season is not so clear anymore. Some days may have a mean temperature lower than the balance point temperature (heating with low energy need– even below 0.5 kWh), while some subsequent days may have a higher mean outdoor temperature than the balance point temperature of the room/building.

A3.3 The radiators were chosen from the product catalogue [27]. In all cases, 22 K type with 600 mm height was selected. That radiator was selected which has a length equal to or almost equal to the size of the window. Radiators are placed below the window (the parapet height is 900 mm). From a thermal point of view, windows are the weak points of the external envelopes, having a higher overall heat transfer coefficient than external walls. In the past when the windows' overall heat transfer coefficient was much higher (2–3 W/m^{2}K) low inner surface temperatures occurred on the windows. To compensate for their lower inner surface temperature radiators were located under the windows (the rising warm airflow improved the situation and provided a warm air curtain between indoors and the window with lower surface temperature). Because of low airtightness, the infiltration was significant and the cold outdoor air entering the room was mixed with the warm air flow rising from the radiator. The design practice of choosing the length of the radiator at least equal to the width of the window was developed decades ago when condensation occurred on the internal surface of the window many times during a heating season. The condensed water was removed from the windows' inner surface by the warm air flow rising from the radiators. Nowadays, because of better thermal and air tigtness properties of building envelopes the size of radiators could be lowered, and the length of radiators might be shorter than the width of the windows. However, the aforementioned design practice is still "in force" and the designers choose the length of the radiators equal or almost equal to the windows width and better decrease the operation temperature of the heating system. This is "rule of thumb" used by designers, not prescribed by design books or standards.

Data availability

Data will be made available on request.

References

[1] S. Garimella, K. Lockyear, D. Pharis, O. El Chawa, M.T. Hughes, G. Kini, Realistic pathways to decarbonisation of building energy systems, Joule 6 (2022) 956–971.

[2] C. Camarasa, É. Mata, J.P.J. Navarro, J. Reyna, P. Bezerra, G.B. Angelkorte, W. Feng, F. Filippidou, S. Forthuber, C. Harris, N.H. Sandberg, S. Ignatiadou, L. Kranzl, J. Langevin, X. Liu, A. Müller, R. Soria, D. Villamar, G. Prata Dias, J. Wanemark, K. Yaramenka, A global comparison of building decarbonisation scenarios by 2050 towards 1.5–2 °C targets, Nat. Commun. 13 (2022) 3077, https://doi.org/10.1038/s41467-022-29890-5.

[3] R. Yan, M. Ma, N. Zhou, W. Feng, X. Xiang, C. Mao, Towards COP27: decarbonization patterns of residential building in China and India, Appl. Energy 352 (2023) 122003.

[4] G. Paoletti, R.P. Pascuas, R. Pernetti, R. Lollini, Nearly zero energy buildings: an overview of the main construction features across europe, Buildings 7 (2017) 43, https://doi.org/10.3390/buildings7020043.

[5] V. Deshko, I. Bilous, I. Sukhodub, O. Yatsenko, Evaluation of energy use for heating in residential building under the influence of air exchange modes, J. Build. Eng. 42 (2021) 103020.

[6] D. Ürge-Vorsatz, L. Cabeza, S. Serrano, C. Barreneche, K. Petrichenko, Heating and cooling energy trends and drivers in buildings, Renew. Sustain. Energy Rev. 41 (2015) 85–98.

[7] D. D'Agostino, L. Mazzarella, What is a Nearly zero energy building? Overview, implementation and comparison of definitions, J. Build. Eng. 21 (2019) 200–212.

[8] D. D'Agostino, S.T. Tzeiranaki, P. Zangheri, P. Bertoldi, Assessing nearly zero energy buildings (NZEBs) development in europe, Energy Strategy Rev. 36 (2021) 100680.

[9] K.N. Rhee, K.W. Kim, A 50 year review of basic and applied research in radiant heating and cooling systems for the built environment, Build. Environ. 91 (2015) 166–190.

[10] J. Oravec, S. Sikula, M. Krajcík, M. Arıcı, M. Mohapl, A comparative study on the applicability of six radiant floor, wall, and ceiling heating systems based on thermal performance analysis, J. Build. Eng. 36 (2021) 102133.

[11] K.N. Rhee, B.W. Olesen, K.W. Kim, Ten questions about radiant heating and cooling systems, Build. Environ. 112 (2017) 367–381.

[12] A. Hesaraki, N. Huda, A comparative review on the application of radiant low-temperature heating and high-temperature cooling for energy, thermal comfort, indoor air quality, design and control, Sustain. Energy Technol. Assessments 49 (2022) 101661.

[13] M. Bojic, D. Cvetkovic, V. Marjanovic, M. Blagojevic, Z. Djordjevic, Performances of low temperature radiant heating systems, Energy Build. 61 (2013) 233–238.

[14] M. Krajcík, M. Arıcı, O. Šikula, M. Šimko, Review of water-based wall systems: heating, cooling, and thermal barriers, Energy Build. 253 (2021) 111476.

[15] R. Li, T. Yoshidomi, R. Ooka, B.W. Olesen, Field evaluation of performance of radiant heating/cooling ceiling panel system, Energy Build. 86 (2015) 58–65.

[16] T. Kalmár, B. Bodó, F. Kalmár, Heat losses of low-temperature radiant heating systems, Energy Rep. 10 (2023) 1982–1995.

[17] M.S. Shin, K.N. Rhee, S.R. Ryu, M.S. Yeo, K.W. Kim, Build. Environ. 92 (2015) 559–577.

[18] M. Krajcík, M. Šimko, O. Šikula, D. Szabó, D. Petráš, Thermal performance of a radiant wall heating and cooling system with pipes attached to thermally insulating bricks, Energy Build. 246 (2021) 111122.

[19] M.R. Safizadeh, M. Schweiker, A. Wagner, Experimental evaluation of radiant heating ceiling systems based on thermal comfort criteria, Energies 11 (2018) 2932, https://doi.org/10.3390/en11112932.

[20] P. Ding, Y. Li, E. Long, Y. Zhang, Q. Liu, Study on heating capacity and heat loss of capillary radiant floor heating systems, Appl. Therm. Eng. 165 (2020) 114618.

[21] D. Wang, Y. Liu, Y. Wang, J. Liu, Numerical and experimental analysis of floor heat storage and release during an intermittent in-slab floor heating process, Appl. Therm. Eng. 62 (2014) 398–406.

[22] Y. Karakoyun, O. Acikgoz, A. Çebi, A. Koca, G. Çetin, A.S. Dalkilic, S. Wongwises, A comprehensive approach to analyze the discrepancies in heat transfer characteristics pertaining to radiant ceiling heating system, Appl. Therm. Eng. 187 (2021) 116517.

[23] A. Koca, Z. Gemici, Y. Topacoglu, G. Cetin, R. Can Acet, B.B. Kanbur, Experimental investigation of heat transfer coefficients between hydronic radiant heated wall and room, Energy Build. 82 (2014) 211–221.

[24] O. Acikgoz, Y. Karakoyun, Z. Yumurtacı, N. Dukhan, A.S. Dalkılıç, Realistic experimental heat transfer characteristics of radiant floor heating using sidewalls as heat sinks, Energy Build. 183 (2019) 515–526.

[25] A. Koca, G. Cetin, Experimental investigation on the heat transfer coefficients of radiant heating systems: wall, ceiling and wall-ceiling integration, Energy Build. 148 (2017) 311–326.

[26] J. Shinoda, O.B. Kazanci, S. Tanabe, B.W. Olesen, A review of the surface heat transfer coefficients of radiant heating and cooling systems, Build. Environ. 159 (2019) 106156.

[27] https://www.vogelundnoot.com/static_files/uk/media/downloads/31667%20VN%20Technical%20Brochure%20UK%20WEB.pdf. (Accessed 15 April 2024).

[28] EN 16798-1, Energy performance of buildings. Ventilation for buildings Indoor environmental input parameters for design and assessment of energy performance of buildings addressing indoor air quality. Thermal Environment, Lighting and Acoustics. Module M1-6, 2019.

[29] 253/1997 Hungarian Governement Decree on the National Settlement Planning and Construction Requirements.

[30] MSZ 04140/3 Hungarian Standard: Thermal calculation of buildings and buildings envelope. Calculation of Heat Demand (Retracted in 2012).

[31] 7/2006 TNM Decree, Energy Performance of Buildings (Retracted in 2023), 2006.

[32] 9/2023 EKM Decree, Energy Performance of Buildings, 2023.

[33] EN ISO 52016-1:2017: energy performance of buildings - energy needs for heating and cooling, Internal Temperatures and Sensible and Latent Heat Loads - Part 1: Calculation Procedures.

[34] Y.G. Yohanis, B. Norton, Utilization factor for building solar-heat gain for use in a simplified energy model, Appl. Energy 63 (1999) 227–239.

[35] ISO 7730:2005, 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.

[36] P.O. Fanger, Thermal Comfort: Analysis and Applications in Environmental Engineering, Danish Technical Press, Copenhagen, 1970.

[37] L. Bánhidi, The thermotechnical dimensioning of radiant strips and borders for the heating of communal buildings, Building Sciences 9 (1974) 85–90.

[38] Hungarian meteorological Service database. https://met.hu/en/idojaras/. (Accessed 18 December 2023).

[39] B. Lin, Z. Wang, H. Sun, Y. Zhu, Q. Ouyang, Evaluation and comparison of thermal comfort of convective and radiant heating terminals in office buildings, Build. Environ. 106 (2016) 91–102.