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Research paper

Heat losses of low-temperature radiant heating systems

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ABSTRACT

There is a consensus among stakeholders that nearly zero energy buildings (nzeb's) represent a step forward towards low-carbon societies. The envelope of nzeb's is well insulated, so there are cases when the external building elements are used as radiant heating surfaces (floor, ceiling, and walls). There is little information about the heat losses of the low-temperature radiant heating systems installed on the inner surface of the external opaque building elements. The purpose of this study was to quantify and compare the energy used for heating in the case of traditional radiator heating and three different radiant heating modes. The calculation methodology was validated by laboratory measurements. Three different thermal requirements related to the building envelope have been assumed and two different heat sources, so 24 different cases have been analyzed in detail and the energy used was compared. The switch-on and switch-off temperatures were determined using the heat gains utilization factor calculated on a daily basis. It was shown that the energy used for heating in the case of radiant heating (taking into account the delivered heat and the heat losses) exceeds the energy used in the case of radiator heating. In the case of nzeb's the difference is the highest and may reach even 23.2%–24.8%.

1. Introduction

1.1. Literature review

The building sector is considered to have the highest potential for energy saving, (Anon, 2003). Nearly zero energy buildings (nzeb) are considered to be the first step towards the minimization of carbon dioxide emissions targets in many countries, (Recast, 2010). Besides the cutback of environmental loads, nzeb contributes to the reduction of energy dependency of countries disposing of fewer fossil fuel reserves. In 2011 REHVA proposed a definition of nzeb for uniformed national implementation of EPBD recast and gave the definition of some related notions, (Kurnitski et al., 2011). The technical definition of nzeb was presented through examples by Kurnitski (2013).

In the last one and a half decades, European countries tightened the requirements related to the energy performance of buildings, (Annunziata et al., 2013). However, each country has already a building stock with variable thermo-physical properties of the envelopes and yearly the newly built flats represent less than 1% of the total number of existing houses. Moreover, a quite high number of flats are situated in hundreds of years old buildings characterized by poor thermo-physical properties of the envelope. The energy refurbishment of these old buildings, as a part of the cultural heritage of countries, is still a challenge. For this reason, the decrease in the share of the building sector in the energy profile of some European countries is not as high as expected, (D'Agostino et al., 2021). According to Liu et al. 37 local governments have implemented policies to promote the nzeb in China (Liu et al., 2019b). Both in European countries and China the nzeb is characterized by a low overall heat transfer coefficient of the envelope, improved air tightness, controlled ventilation with heat recovery, and integration of renewable energy sources (mainly PV's, solar collectors, and heat pumps), (Liu et al., 2019a; Paoletti et al., 2017). Over the years new definitions and interpretations were introduced, so D'Agostino and Mazzarella tried to provide an overview of the used definitions, (D'Agostino and Mazzarella, 2019). To further improve the energy performance in the building sector, the next steps were net zero energy buildings and positive energy buildings. Deng et al. provided an overview of net zero energy buildings evaluation, (Deng et al., 2014). They claimed that the impact of the building on the environment should be part of the evaluation. Theoretical bases of positive energy buildings have been presented by Magrini et al. (2020). Through a case study, they demonstrated that an integrated design of the building envelope and systems not only allows to obtain an almost total coverage of the energy consumption by renewable energy sources but also generates an energy surplus that could be shared with urban grids. However, using high-performance insulation materials the variation in time of thermo-physical properties should be taken into account, (Lakatos, 2020). Zero-carbon buildings are the new challenge in the building sector. Zhao and Pan analyzed

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the role of innovative business models in the acceleration of the uptake of the zero-carbon buildings approach, (Zhao and Pan, 2015). They found that customers' awareness and behaviors, and the unstable and ambiguous legislative and economic challenges greatly influence the construction of zero-carbon buildings. Besides these obstacles, carbon emission intensity in the electricity production sector should be further reduced to achieve carbon-neutral buildings (Shi-Cong et al., 2021). Besides the thermal requirements related to building envelope and integration of renewable energy sources, designers should pay attention to indoor comfort and climate change to provide optimal solutions for buildings, (D'Agostino and Parker, 2018). According to Rhee et al. radiant heating and cooling are advantageous both from energy efficiency and thermal comfort point of view, (Rhee et al., 2017). So, the radiant heating and cooling systems can be used successfully in nzeb's. The large surfaces facilitate the use of low water temperatures for heating and high water temperatures for cooling, so renewable energy sources can be successfully used, (Ren et al., 2010). Heating represents the highest share of the total energy consumption of residential buildings in countries with temperate or cold climates, (D'Agostino and Parker, 2018). According to Hesaraki and Huda low-temperature radiant heating systems can save between 10 and 30% energy and provide better thermal comfort compared to the all-air system (Hesaraki and Huda, 2022). Low-temperature heating systems enable the 4th generation of district heating (Østergaard et al., 2022). Nevertheless, the proper control and management of the heating, cooling, and ventilation systems is essential to minimize energy consumption (Borrelli et al., 2021). Because of their advantages low-temperature heating systems have been thoroughly investigated. There are lots of studies analyzing the heat transfer coefficients between the heating surface and air, thermal response, the effect of distance between pipes on the heat flux and surface temperatures, and the effect of the supply and return temperatures on the heat flux and thermal comfort, (Feustel and Stetiu, 1995; Shin et al., 2015; Koca and Cetin, 2017; Wang et al., 2014; Karakoyun et al., 2021; Chen et al., 2021). During the operation of the heating system, a certain part of transmission heat losses can be eliminated if external building elements (floor, walls, ceiling) are used as radiant surfaces (thermal barrier) (Krajcík et al., 2021a). However, the heat losses of the heating system will increase. Li et al. provided in their study information about the heat losses in the case of a radiant heating/cooling suspended ceiling, (Li et al., 2015). In studies related to radiant heating systems, there is little information about the total energy used by radiant heating systems in a whole heating season. Nevertheless, this information is extremely important since low-temperature radiant heating systems are widely used, especially in nzeb's.

1.2. Aim of the study

The utilization of low-temperature surface heating systems has a series of advantages. First of all, the heat demand of the heated room is lowered, since the heat losses through external building elements containing the heating layer are eliminated. Secondly, the supply temperature is reduced because of the larger heating surface. Thirdly, because of the lower supply and return temperatures, the energy efficiency of heat sources (condensing boilers or heat pumps) will be higher. The embedded heating layer splits the building structure, into two parts: the internal side (between the heating layer and internal air) and the external side (between the heating layer and external air). The heating layer modifies the temperature distribution in the building structure. During the operation of the heating system, the heat losses of the system will increase (a certain quantity of heat is lost flowing outdoors through the layers of the external side of the building elements). Because of the higher temperatures, the heat losses of the system will exceed the heat loss through the building element without an embedded heating layer. It is necessary to know the yearly energy balance between the aforementioned energy savings and the higher heat losses in the case of different low-temperature radiant heating systems embedded in external building elements.

The purpose of our study is to determine, analyze, and compare the heat losses and energy used for heating in buildings with different thermal characteristics of the envelope equipped with radiant heating assuming that opaque external building elements are used as radiant heating surfaces. The method and the results can be used by stakeholders for rapid energy analysis and may draw the attention of practitioners to the appropriate design and operation of low-temperature radiant heating systems.

2. Methodology

To establish the energy used for heating, taking into account the thermal inertia of the rooms and the heating system, the calculation was done on a daily basis. The analyzed period of the year was from the 1st of September till the 30th of April (242 days). The research flow chart for this study is shown in Fig. 1.

Hungarian building energy requirements and climate conditions were taken into account. The indoor set point temperature in the building was considered 20 °C, constant during the heating season. According to the current energy performance regulation, the internal heat gains have been assumed at 5.0 W/m^2, (Anon, 2006).

2.1. Building

In most European countries the energy performance requirements have changed in the last two decades. In Hungary, the set of requirements was tightened two times in this period of time. Obviously, there are millions of flats built before the year 2000, but in these buildings, the use of radiant heating is not widely used. The relatively high heat demand is the reason why only radiant floor heating can be found in some buildings older than 20 years.

Usually, in those rooms where floor heating was installed, this heating mode was used in combination with radiators to cover heat demand. After the year 2000, investors and building owners endeavoured to build buildings with lower energy needs and used building materials with better thermo-physical properties, (Szodrai and Lakatos, 2015). At the same time, to improve the thermal comfort level, more and more buildings were equipped with radiant heating (especially floor heating, but ceiling- and wall heating can be found as well in buildings built after the year 2000). Nowadays, in most buildings radiant heating is installed (either floor or ceiling or wall heating, or all of these).

Since 2006, the requirement related to the energy performance of buildings has three levels: the first level is related to the overall heat transfer coefficient of the external building elements, the second requirement is related to the specific heat loss, and the third level is related to the annual specific primary energy use. The set of three levels of requirements has to be fulfilled concomitantly. Table 1 shows the requirements for three different years in the last two decades.

The requirement related to specific heat losses (2nd level) is established depending on the ratio of building envelope area and heated volume ($\Sigma A/V$). Q_{sd} and Q_{sid} are the direct and indirect solar heat gains of the building, in [Wh], while H is the heating degree day in [hK].

The transmission heat loss coefficient of the building is:

$$K_{tr} = \sum AU + \sum \Psi l \qquad [\mathrm{W/K}] \qquad (1)$$

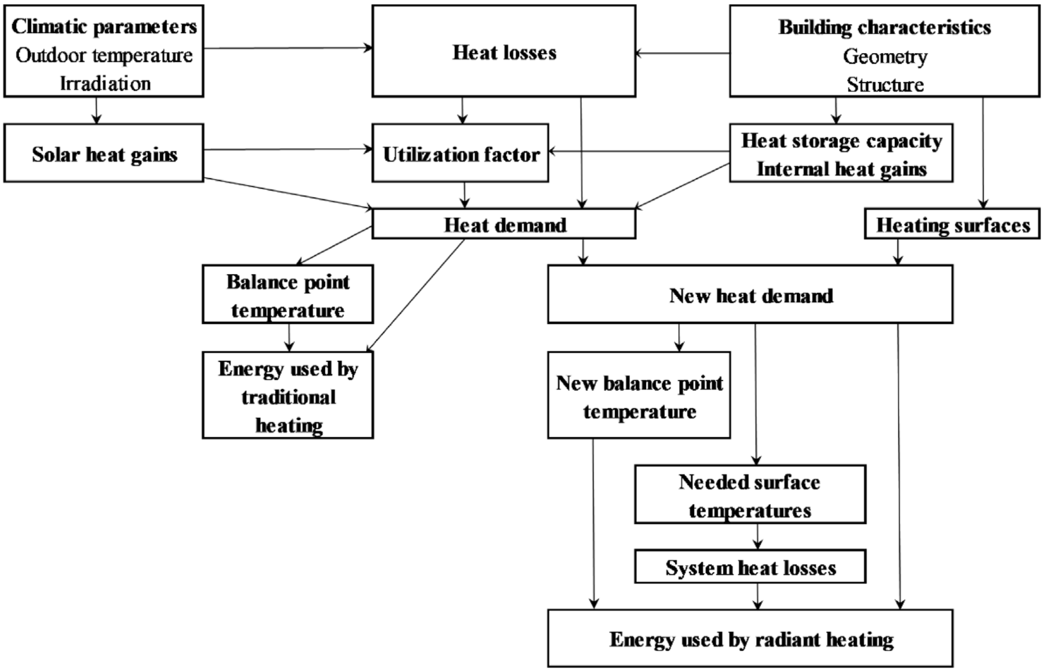

Fig. 1. Steps of the calculation methodology.

Table 1
Requirements related to the energy performance of buildings.

Years	Requirement	
2002	U_{wall}, [W/m^{2}K]	0.7
	U_{slab}, [W/m^{2}K]	0.4
	U_{window}, [W/m^{2}K]	3.0
	U_e, [W/m^{2}K]	2.0
	q, [W/m^{3}K]	$q = \frac{K_{tr}}{V} \leq 0.6\frac{\sum A}{V} + 0.1$
2012	U_{wall}, [W/m^{2}K]	0.45
	U_{slab}, [W/m^{2}K]	0.25
	U_{window}, [W/m^{2}K]	1.60
	q, [W/m^{3}K]	$q = \frac{1}{V}\left(K_{tr} - \frac{Q_{sd}+Q_{sid}}{H}\right) \leq 0.38\frac{\sum A}{V} + 0.086$
	E_p, [kWh/m^{2}a]	$120\frac{\sum A}{V} + 74$
2022 (nzeb's)	U_{wall}, [W/m^{2}K]	0.24
	U_{slab}, [W/m^{2}K]	0.17
	U_{window}, [W/m^{2}K]	1.15
	q, [W/m^{3}K]	$q = \frac{1}{V}\left(K_{tr} - \frac{Q_{sd}+Q_{sid}}{H}\right) \leq 0.2296\frac{\sum A}{V} + 0.05143$
	E_p, [kWh/m^{2}a]	100
	25% of E_p must be assured from RES	

where: A — is the area of an external building element, [m^2]; U is the overall heat transfer coefficient of the external building element, [W/m^{2}K]; Ψ — is the linear heat transfer coefficient of a thermal bridge, [W/mK]; l — is the length of the thermal bridge, [m].

From 2006 all possible external building elements are listed in the decree, but in this study, only the most frequent building elements were taken into account.

In Hungary, there is no requirement related to the air tightness of buildings, but a 0.5 h^{-1} air change rate is considered in the energy performance calculations, according to the current regulation (Anon, 2006).

The case study calculations have been performed using the geometry of an existing building, built in 2002, (Fig. 2). The building is a detached single-family house, which has an unheated cellar under the whole floor and an unheated attic (the net heated floor area is equal to floor area and slab area).

The building fulfills the requirements applied before 2006 but to provide a comparison from an energy point of view between buildings constructed in different years of the last two decades, the thermal properties of the envelope have been changed for calculations according to Table 1. The main geometry data of the building are shown in Table 2.

2.2. Climate

The energy used for heating strongly depends on weather patterns during the heating season. D'Agostino et al. investigated the impact of climate change on the design and energy performance of nzeb's, (D'Agostino et al., 2022). The study revealed that the temperature has increased over recent decades in all evaluated locations. Our previous studies proved that the outdoor dry bulb design temperatures should be re-examined in Hungary as well, (Verbai et al., 2015). To provide reliable results in this

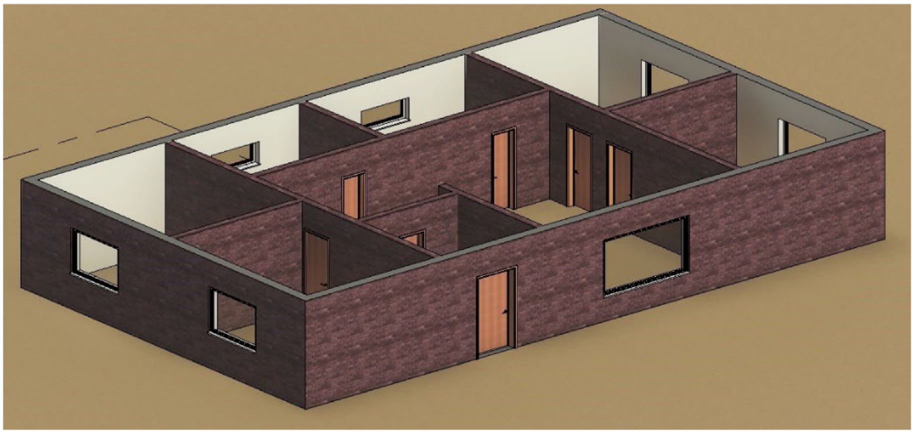

Fig. 2. Analyzed building.

Table 2
Main parameters of the building.

Parameter		Value
Net heated floor area, [m^2]		154.48
Heated volume, [m^3]		432.54
ΣA/V, [m^{-1}]		1.1
Windows/door surfaces, [m^2]	S	4.05
	E	4.32
	W	4.32
	N	0.9
WWR, [%]	S	8.8
	E	15.4
	W	15.4
	N	0.028
Thermal mass, [kg]		49923

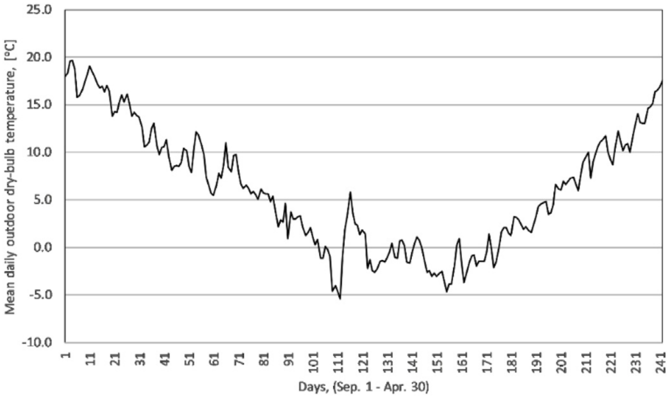

Fig. 3. Daily mean outdoor dry bulb temperatures.

study, the hourly outdoor temperatures and solar radiation data for five years (2009–2013) have been procured, from the Meteorological Observatory, University Debrecen (Hungary). The daily mean values of the outdoor temperatures and irradiation on the south (S), east (E), west (W), and north (N) orientations of the facades have been determined. The average climate parameters used for energy calculations carried out in this study have been determined using the mean daily values of the years 2009–2013 from the 1st of September to the 30th of April for each year. The daily variation of the irradiation on a façade with a certain orientation during a specific day of the analyzed months can be seen in the Appendix (Figs. A.1–A.4). The daily mean temperatures can be seen in Fig. 3.

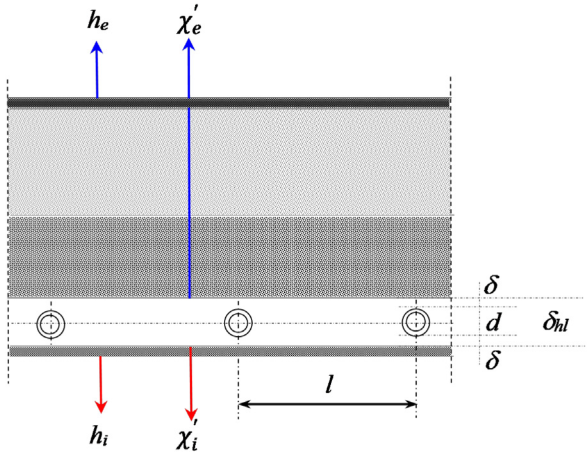

Fig. 4. Section of the radiant building element.

2.3. Surface temperatures

In order to help in understanding the process and the used notations the vertical section of a radiant building element is presented in Fig. 4.

The pipes are embedded in the structure of the building element as close as possible to the inner surface. The surface over-temperature (the temperature above the indoor air temperature, t_i) of the heating layer can be determined with the Kollmar relation, (Bánhidi, 1974):

$$\theta'_m = \frac{\theta_w th\frac{ml}{2}}{\left(1 + h_i\frac{\delta}{\lambda}\right)\frac{ml}{2}} \quad (2)$$

where: δ — is the thickness of the pipes covering layer, [m]. The θ_w — is the average over-temperature of the heating fluid:

$$\theta_w = \frac{t_s + t_r}{2} - t_i \qquad [\mathrm{K}] \quad (3)$$

while the coefficient m is:

$$m = \frac{\chi'_i + \chi'_e}{\delta_{hl}\lambda} \quad (4)$$

where: t_s — is the supply temperature [°C]; t_r — is the return temperature, [°C]; δ_{hl} — is the thickness of the heating layer, [m]; λ — is the heat conductivity of the heating layer material, [W/mK].

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

$$\chi_i' = \frac{1}{\frac{1}{h_i} + \frac{\delta_p}{\lambda_p}} \tag{5}$$

where h_i – is the heat transmittance on the internal surface of the building element, [W/m^{2}K]; δ_p – is the thickness of the plaster covering the heating layer, [m]; λ_p – is the heat conductivity of the plaster 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:

$$\chi_e' = \frac{1}{\frac{1}{h_e} + \sum_{j=1}^{n} \frac{\delta_j}{\lambda_j}} \tag{6}$$

where h_e – is the heat transmittance 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 mean inner surface over-temperature of the radiant building element will be:

$$\theta_{mi} = \theta_m' \frac{\chi_i'}{h_i} \tag{7}$$

2.4. Energy used for heating

The specific heat released by the radiant building element to the room can be determined with relation:

$$\dot{q}_i = h_i \theta_{mi} \qquad [\mathrm{W/m^2}] \tag{8}$$

The specific heat losses can be calculated using Eq. (9):

$$\dot{q}_e = \theta_m' \chi_e' \qquad [\mathrm{W/m^2}] \tag{9}$$

The daily energy needed for heating ($\dot{Q}_{totd}$) is the sum of heat released in the room/building and the heat losses:

$$\dot{Q}_{totd} = 0.024 \sum A_j \left(\dot{q}_i + \dot{q}_e\right)_j \qquad [\mathrm{kWh}] \tag{10}$$

where: A_j – is the net area of the radiant external building element (floor, ceiling, or wall).

The energy needed for heating in a heating season will be the sum of the daily energy needs:

$$\dot{Q}_{tot} = \sum_{j=1}^{N} \dot{Q}_{totdj} \qquad [\mathrm{kWh}] \tag{11}$$

where: N is the number of heating days in a heating season.

Obviously, the balance point temperature and the number of heating days ought to be determined.

To calculate the balance point temperature, the useful heat gains have to be determined first. According to Yohanis and Norton the heat gains utilization factor η_H can be determined using Eq. (12), (Yohanis and Norton, 1999):

$$\eta_H = 1 - e^{\frac{-k}{\gamma_H - D}} \tag{12}$$

where k and D are correlation coefficients. For these coefficients, Yohanis and Norton proposed the following relations, (Yohanis and Norton, 1999):

$$k = 1,0785 + 0,0041\tau - 6 \times 10^{-7}\tau^2 \tag{13}$$

$$D = -0,0087 - 0,007\tau + 7 \times 10^{-8}\tau^2 \tag{14}$$

where: τ is the room/building zone/building time constant, determined according to EN ISO 52016-1, (Anon, 2017).

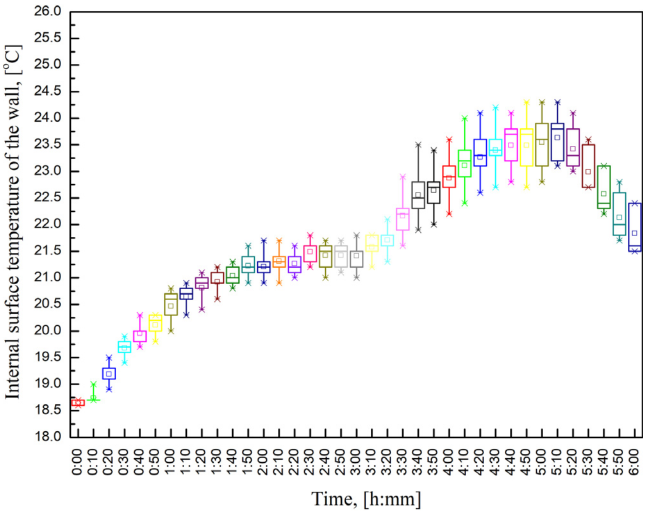

Fig. 5. Inner surface temperature of the radiant wall.

2.5. Validation of the calculation method

To validate the calculation methodology presented in (2.3) a series of measurements have been performed in the Indoor Environment Quality laboratory of the University of Debrecen. In the laboratory, there is a climate chamber in which the test room is placed. The internal dimensions of the test room are 2.49 m in width, 3.65 m in length, and 2.56 m in height. In the test room floor-, wall-, ceiling, and radiator heating is possible. Around the test room, different temperatures can be set between −15 °C and +35 °C.

The length of the experiment was 6.0 h. The heating of the test room was provided through one of the external walls. Starting from the internal surface the layers of the wall are the following: 1.5 cm lime mortar (λ = 0.81 W/mK), 1.5 cm lime mortar (heating layer with 14 mm diameter pipes), brick (λ = 0.78 W/mK) and 1.5 cm lime mortar. The indoor temperature was set to +20 °C, while the "outdoor" temperature was set to +10 °C. The supply/return temperatures were 31 °C/24 °C, but after three hours was changed to 40 °C/32 °C. In the last hour, the heating system was switched off. The radiant wall inner and outer surface temperatures have been measured both with Testo 905 T2 (in 9 different locations) and thermocamera Testo 882. The variation of the inner surface temperatures can be seen in Fig. 5.

The outer surface temperatures are shown in Fig. 6.

It ca be stated that the steady state process can be considered between hours 2:00–3:00. The heat losses of the wall heating system are presented in Fig. 7 (mean value 27.04 W/m^2, SD = 0.8)

Using the presented calculation method, the heat losses of the radiant wall are 26.36 W/m^2. The difference is 2.5%, which is acceptable in practice. Without the built-in heating layer, the heat losses of the wall would be 17 W/m^2.

3. Results

Comparing the degree day curve used currently for energy calculations and the degree day curve determined for the analyzed five years (Fig. 8) differences can be identified especially at low outdoor temperatures (the coldest 10 days).

It should be mentioned that currently there are three regions with different outdoor design temperatures in Hungary. In Debrecen, the outdoor design temperature for heating systems is −15 °C. The warm period was not analyzed in this study, but the

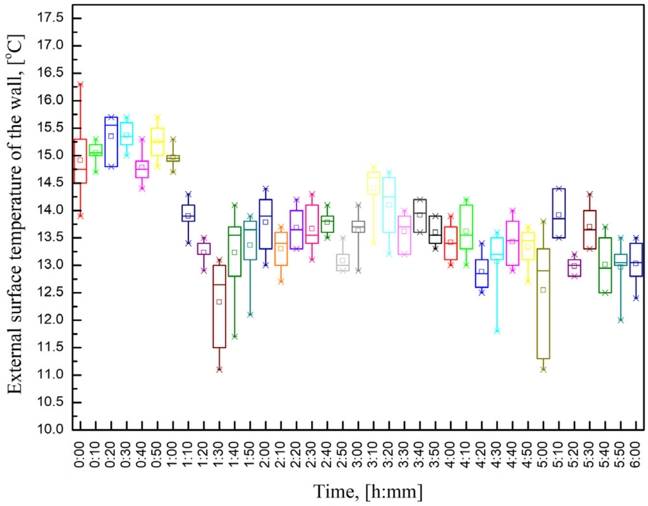

Fig. 6. Outer surface temperature of the radiant wall.

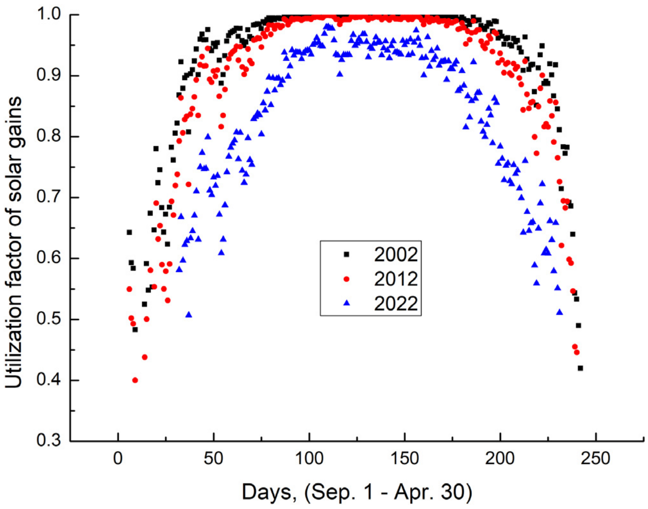

Fig. 9. Utilization factors for analyzed buildings.

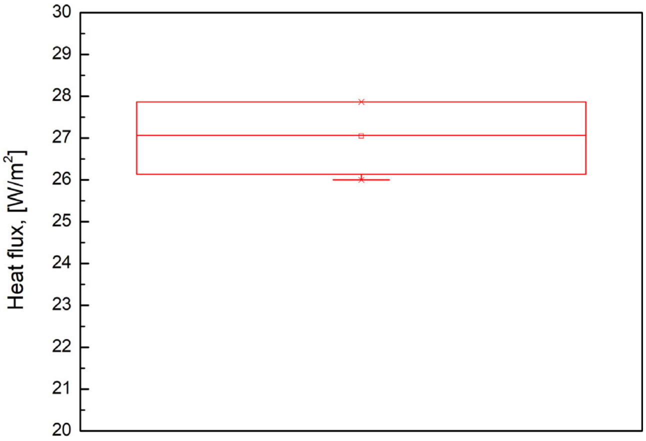

Fig. 7. Heat losses of the radiant wall.

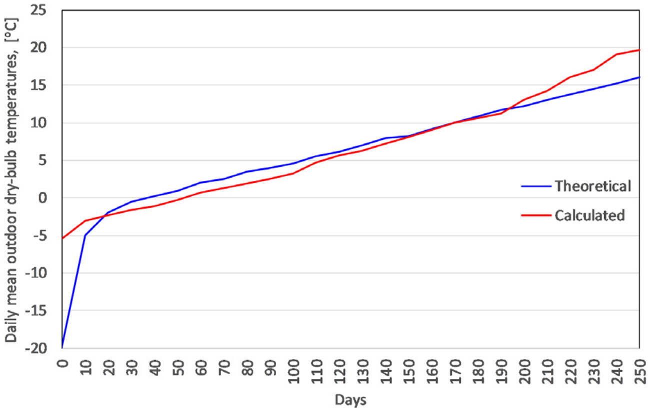

Fig. 8. The theoretical and the calculated (2009–2013) degree day curve (heating season).

trend of the temperature curve reveals that probably the warmest days have been characterized by higher average temperatures in the analyzed five-year period. These results agree well with the statements of previous studies (D'Agostino et al., 2022).

Having different characteristics of the envelope, the heat losses of the analyzed buildings are different. As a consequence, the utilization factor of heat gains and the time constant is not similar for analyzed cases even though the thermal mass and the heat storage capacity are identical. The daily values of the utilization factor from the 1st of September to the 30th of April period of time have been calculated and presented in Fig. 9. It can be observed that the utilization factor of heat gains decreases for better thermal properties of the envelope (the nzeb's are characterized by the lowest values of the utilization factor). Furthermore, lower utilization factor values should be taken into account at the beginning and at the end of the heating season (lower heat losses and higher solar heat gains).

Based on the incident solar radiation values, internal heat gains and utilization factor the useful heat gains can be determined. The daily variation of heat losses and heat gains for analyzed buildings are presented in Fig. 10. The first intersection of the two curves corresponds to the starting day of the heating season, while the second intersection shows the end of the heating season.

The area between the heat losses and heat gains represents the energy need for heating. It can be observed that the length of the heating season decreases only 6 days while the energy needed for heating decreases by 31.4% for the first step of energy performance 2002–2012. In the second step of requirements tightening (2012–2022) the energy need for heating decreases by 67.7%, while the heating season is shorter by 33 days. Assuming that the energy needed for heating is delivered by a condensing boiler or an air–water heat pump the primary energy use was determined. Currently, in the calculation of primary energy the conversion factor is 1.0 for natural gas and 2.5 for electricity (Anon, 2006). The temperature control curve (traditional radiator heating) is presented in Fig. A.5. The efficiency of the boiler was determined daily using the data provided by Satyavada and Baldi (2016). The COP for the air–water heat pump has been taken from Hirvonen and Sirén (2017). The design supply/return temperatures in the case of radiant heating have been calculated using Eqs. (3)–(9) and are presented in Table A.2. The energy used by the heating systems was calculated daily depending on the outdoor temperature, supply–return temperature, and the corresponding efficiency of the boiler or heat pump. The calculated data are presented in Table 3.

It can be observed that the balance point temperature for starting the heating system is not equal to the temperature when the heating is stopped. This is caused by the fact the outdoor temperature and solar gains variation in September–October are not

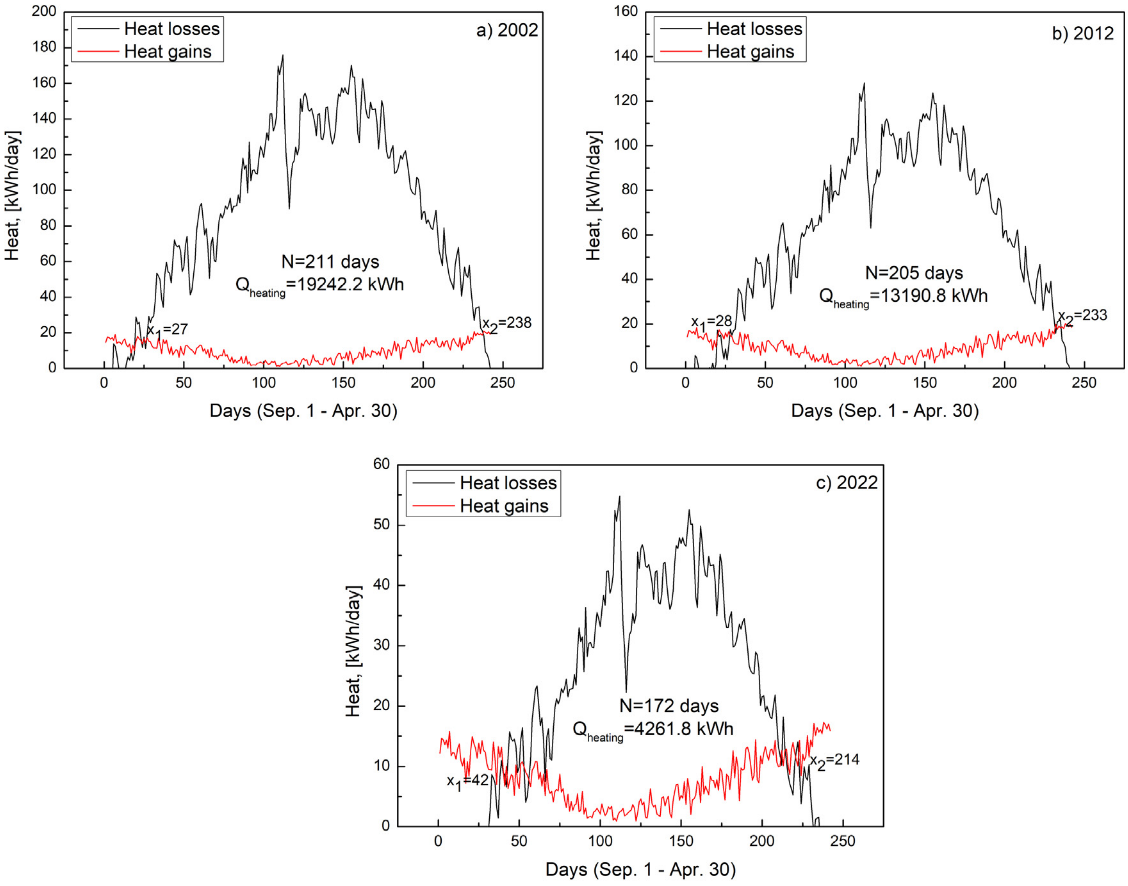

Fig. 10. Energy need for heating (a) 2002; (b) 2012; (c) 2022.

Table 3
Energy used for heating in the case of radiators.

	2002	2012	2022
Outdoor start temperature for heating, [°C]	15.1	13.7	9.6
Outdoor stop temperature for heating, [°C]	14.8	13.0	9.0
Number of heating days, [days]	211	205	172
Energy need for heating, [kWh]	19242.2	13190.8	4261.8
Energy used for heating (condensing boiler), [kWh]	20578	14106.3	4578
Energy used for heating (air–water heat pump), [kWh]	6673.4	4592	1511.5
Primary energy used for heating (condensing boiler), [kWh]	20578	14106.3	4578
Primary energy used for heating (air–water heat pump), [kWh]	16683.5	11480	3778.8

exactly equal (day by day) to the outdoor temperature and solar gains in March–April. The switching off outdoor temperature is a little bit lower than the switching on temperature (meaning that the solar gains in the spring season exceeded the solar gains in autumn).

Installing heating surfaces on the external opaque building elements (floor, ceiling, and walls) a thermal barrier is inserted and the building's heat losses are reduced. This means that under the same climatic conditions, the balance point temperature will be lower. However, it assumes that the temperature of the external building elements is at least equal (or higher) than the indoor set-point temperature. The needed surface temperature is obtained by circulating in the heating system a heat carrier (water) with a higher temperature than the indoor set-point temperature. This higher temperature is leading to the increase of the heat losses through these external building elements (the heat losses of the heating system will be higher than the heat losses through the building elements without radiant surfaces). Fig. 11 shows the heat delivered in the building by the heating surfaces, heat losses of the system to the outdoors (outdoor air, attic, cellar), and the total energy needed for heating. It can be seen in all analyzed cases the heat losses exceed the heat delivered by the radiant surfaces in the heated spaces.

The calculated energy data are presented in Table 4. In the case of radiant heating two balance outdoor temperatures should be mentioned. The first one is related to switching on and switching off the heating system, while the second one is related to starting and ending the heat delivery in the heated rooms.

It can be observed that in all cases the energy used for heating is higher than the energy used in the case of traditional heating systems with radiators. Using condensing boilers for heat generation the increments are 5.6% (2002 and 2012) and 23.2% in the case of nzeb's (2022). Assuming that the heat generator is an air–water heat pump the increments are 8.02% (2002), 7.87% (2012), and 24.79% respectively in the case of nzeb's (2022).

Obviously, in all analyzed cases it was assumed that all external building elements are provided with heating surfaces. This is an extreme situation. But in any other case (combination of floor and ceiling heating or only floor heating) the heat carrier (warm water) temperature should be increased because the heating surface was reduced. To see the differences between the heat losses

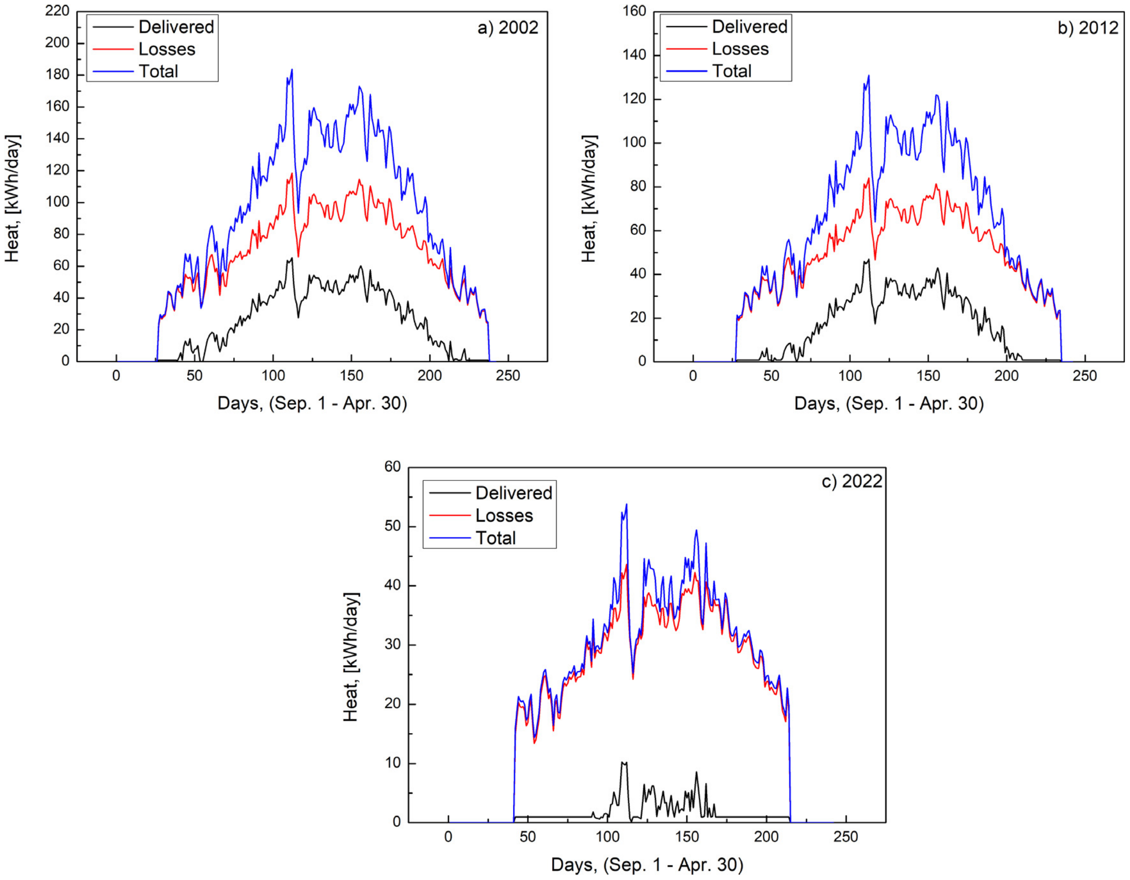

Fig. 11. Daily energy demand for heating (a) 2002; (b) 2012; (c) 2022.

Table 4
Energy used for heating in the case of radiant heating (1st scenario).

	2002	2012	2022
Outdoor switch-on temperature for heating, [°C]	15.1	13.7	9.6
Outdoor start temperature for heat delivery, [°C]	10.5	9.6	1.0
Outdoor switch-off temperature for heating, [°C]	14.8	13.0	9.0
Outdoor stop temperature for heat delivery, [°C]	8.7	7.5	−1.5
Number of operation days of the heating system, [days]	211	205	172
Number of heating days, [days]	176	161	75
Energy needed for heating, [kWh]	5689.9	3611.8	342.8
System losses, [kWh]	15180.1	10700.7	5073.4
Total energy need, [kWh]	20870	14312.5	5416.2
Energy used for heating (condensing boiler), [kWh]	21739.6	14908.9	5641.8
Energy used for heating (air–water heat pump), [kWh]	7208.6	4953.4	1886.3
Primary energy used for heating (condensing boiler), [kWh]	21739.6	14908.9	5641.8
Primary energy used for heating (air–water heat pump), [kWh]	18021.5	12383.5	4715.8

in the case of larger surfaces and lower temperatures versus smaller surfaces and lower temperatures two situations were further analyzed: floor heating combined with ceiling heating (2nd scenario) and only floor heating (3rd scenario). The results are presented in Figs. A.7–A.8 and in Tables 5 and 6.

It can be observed that the switch-on and switch-off temperatures for heating are not changed, while both the starting and ending temperatures for heat delivery are higher. This means a longer heating season and a higher amount of heat delivered in the building than the values obtained in the previously analyzed case. However, the heat losses of the heating system decrease substantially. The primary energy used for heating became lower both in the case of the condensing boiler and the heat pump. When only the floor heating is installed, the longest heating season but the lowest energy use is obtained for radiant heating.

4. Discussion

It was proven that low-temperature radiant heating systems are advantageous from thermal comfort point of view in comparison with "traditional" convective heating systems with radiators, (Olesen, 2002; Lin et al., 2016). The performances of radiant heating solutions have been analyzed both from energy and exergy points of view, (Bojic et al., 2013; Sattari and Farhanieh, 2006). However, is little known about what happened with the heat losses when these systems are installed. In many studies, the heat transfer on the inner side of the heating surfaces is analyzed. Nevertheless, by introducing a layer with a higher temperature in the structure of an external building element, the heat transferred to the external environment (heat losses) will increase. Obviously, by increasing the heating surfaces the supply–return temperatures of the central heating systems can be

Table 5
Energy used for heating in the case of floor and ceiling heating (2nd scenario).

	2002	2012	2022
Outdoor switch-on temperature for heating, [°C]	15.1	13.7	9.6
Outdoor start temperature for heat delivery, [°C]	13.9	10.6	8.0
Outdoor switch-off temperature for heating, [°C]	14.8	13.0	9.0
Outdoor stop temperature for heat delivery, [°C]	13.1	10.0	4.5
Number of operation days of the heating system, [days]	211	205	172
Number of heating days, [days]	202	197	125
Energy needed for heating, [kWh]	11299	7549.3	1706.6
System losses, [kWh]	8739.5	6139.6	2948.5
Total energy need, [kWh]	20038.5	13688.9	4655.2
Energy used for heating (condensing boiler), [kWh]	20873.4	14259.3	4849.1
Energy used for heating (air–water heat pump), [kWh]	6934.6	4753.8	1635.3
Primary energy used for heating (condensing boiler), [kWh]	20873.4	14259.3	4849.1
Primary energy used for heating (air–water heat pump), [kWh]	17336.5	11884.5	4088.3

Table 6
Energy used for heating in the case of floor heating (3rd scenario).

	2002	2012	2022
Outdoor switch-on temperature for heating, [°C]	15.1	13.7	9.6
Outdoor start-temperature for heat delivery, [°C]	13.7	13.4	7.4
Outdoor switch-off temperature for heating, [°C]	14.8	13.0	9.0
Outdoor stop-temperature for heat delivery, [°C]	13.0	12.9	7.25
Number of operation days of the heating system, [days]	211	207	172
Number of heating days, [days]	208	201	153
Energy needed for heating, [kWh]	15014.3	10295.2	2931.8
System losses, [kWh]	4912.1	3234	1465
Total energy need, [kWh]	19926.4	13529.2	4396.8
Energy used for heating (condensing boiler), [kWh]	20756.7	14092.9	4580
Energy used for heating (air–water heat pump), [kWh]	6898.7	4702.6	1551.9
Primary energy used for heating (condensing boiler), [kWh]	20756.7	14092.9	4580
Primary energy used for heating (air–water heat pump), [kWh]	17246.7	11765.5	4655.7

reduced. But in the case of well-insulated buildings or nearly zero energy buildings, the heat demand of rooms can be covered with lower supply–return temperatures even in the case of radiators, so the differences in the supply–return temperatures are not so large. Moreover, using a qualitative control the decrease of the supply–return temperatures will be higher in the case of "traditional" heating with radiators than in the case of radiant heating. The daily efficiency of a condensing boiler or a heat pump is higher for lower supply/return temperatures, so the radiant heating mode is advantageous. However, for partial heat loads, the efficiency of these heat generators increases and the increase of the efficiency for "traditional" heating with radiators is a little bit higher (because the temperature of the heating fluid decreases in a larger amount). In the case of nearly zero energy buildings with well-insulated external building elements, the mean radiant temperature will be obviously higher in comparison with a poorly insulated building. One of the most important advantages of radiant heating systems is the higher mean radiant temperature in comparison with radiator heating and the same operative temperature can be obtained with a lower air temperature. In the case of nearly zero energy building the surface temperatures of external building elements will be higher in comparison with poorly insulated buildings. Higher mean radiant temperatures are obtained in well-insulated buildings as well in the case of radiant heating systems, but the differences are not as high as have been in poorly insulated buildings. Moreover, by using innovative ventilation solutions with special air terminal devices the ventilation rate can be substantially reduced, (Szekeres et al., 2022; Csáky, 2020). Obviously, the ventilation heat losses are minimized in this case, so the energy saving ensured by radiant heating in comparison with convective heating (or traditional radiator heating) decreases.

Assuming a detached house with a certain geometry but with different thermal properties of the envelope corresponding to three different periods of time in Hungary (2002, 2012, and 2022) the energy needed for heating was determined. Taking as basic version the building built in 2002 the heat demand in 2012 was lower by 31.4%, while the heat demand of the building built in the year 2022 (nzeb's) was lower by 77.7%. The energy calculations have been carried out taking into account the hourly meteorological data (dry bulb temperature and global solar radiation) obtained from the Meteorological Observatory, University of Debrecen for five years (2009–2013). Besides the traditional "radiator" heating three different radiant heating modes have been analyzed. In the first case, it was assumed that all external opaque building elements are used as radiant surfaces, in the second case the floor and ceiling heating combination was considered and at the end, only floor heating was assumed.

The results obtained in this study agree well with the results presented by Cvetkovic and Bojic (2014). In the mentioned paper different radiant heating modes were compared and it was shown that the highest insulation thickness is needed in the case of wall heating, while the smallest optimal insulation thickness was obtained in the case of floor heating. With the elimination of wall heating and using the combined floor–ceiling heating (2nd scenario) the energy used for heating, using a condensing boiler, decreased by 3.98% (2002); 4.36% (2012), and 14.05% (2022), while using air–water heat pump the energy saving was 3.8% (2002); 4.03% (2012) and 13.3% (2022) in comparison with the 1st scenario. In the case of the 3rd scenario (only floor heating) the energy use decreased by 4.52% (2002); 5.47% (2012) and 18.82% (2022) having condensing boiler as a heat generator in comparison with the 1st scenario (wall–ceiling–floor heating). With an air–water heat pump, the decrease in energy use is 4.3% (2002); 5.06% (2012), and 17.72% (2022).

Li et al. showed that in the case of a suspended radiant ceiling, the upward heat flux from the panels was as large as 30%–40% of the water heating/cooling capacity, (Shin et al., 2015). These data agree well with our results since in the case of floor heating (3rd scenario), the heat losses of the heating system are 24.6% (2002) and 33.3% (2022). However, using the floor and the ceiling for heating (2nd scenario) the heat losses represent 43.6% (2002)

and 63.3% (2022) of the total energy needed for heating. Finally, in the case of the 1st scenario (all opaque external building elements used for radiant heating), the heat losses are 72.7% (2002) and 93.6% (2022) from the total energy needed for heating. Furthermore, the obtained results agree well with the results obtained by Krajcík et al. (2021b). Performing measurements and detailed simulations they analyzed the energy performance of a wall heating system. The external surface temperature exceeds to a small extent the case when no heating layer was embedded in the wall structure. This means an extremely small increase in heat losses. In our case, (nzeb's and 1st scenario) for the whole heating season the average values of daily heat losses were: 0.05187 kWh/m^2 for the wall heating, 0.02824 kWh/m^2 for the ceiling heating, and 0.02788 kWh/m^2 for the floor heating. These values are small and the differences between the heat losses through the building structures with and without the embedded heating layer seem to be negligible. However, in the case when the heating layer is embedded in the building structure the heat loss is related to the heating system, while in the case of a building structure without an embedded heating layer the heat loss is related to the building. These specific values have to be multiplied by the external wall surface, the ceiling, and the floor surfaces, and finally, the obtained values have to be multiplied again by the number of heating days. That is the reason why, the heat losses of the heating systems represent an important share of the total delivered heat. Similarly, the heat losses through floor, ceiling, and external walls represent an important share of the total heat demand of a building.

It can be stated, that the supply temperature of the heating system can be reduced to a great extent by involving more and more external building elements in the heating process. Moreover, the heat demand of the room is reduced considerably because of the thermal barrier created around the heated spaces. However, the total energy used for heating will increase and the share of the system's heat losses will increase substantially. Obviously, the obtained results are valid in the case of "traditional" low-temperature radiant heating systems. The thermal energy storage and energy performance of these heating systems can be improved by integrating phase change materials in the building elements (Larwa et al., 2021). The heat flow, the temperature distribution in the building structure, and the energy performance of the radiant heating systems can be modified by inserting metal fin between pipes (Oravec et al., 2021). In the case of such special structures, the heat flows cannot be calculated with the presented simplified method.

It should be mentioned that analyzing the required mean surface temperatures (Table A.1) in the case of floor heating the floor temperatures prescribed in Standards (Anon, 2005) are satisfied in all analyzed scenarios. The maximum allowable 29 °C of the floor is not exceeded even in the case of installing only floor heating (2002). However, these high temperatures are required at the design outdoor dry bulb temperature (−15 °C). The required mean temperatures of the radiant systems are presented in Table A.2 and the control curve for floor heating (2002) is presented in Fig. A.6. In the case of radiant floor heating systems exposed to direct solar radiation, the temperature distribution in the building structure is changed, so in order to determine the floor surface temperatures, further calculations are needed (Li et al., 2021).

5. Conclusions

Low-temperature radiant heating systems are widely used in nearly zero energy buildings. The energy performance of these systems is influenced by several factors such as supply/return temperatures, the distance between the pipes, heat transfer coefficients, and the position of the heating layer in the building structure. The heat released by radiant heating systems embedded in building structures depends on the thermal resistance of the layers covering the pipes. The heat losses of the system depend on the thermal resistance of the layers placed under the heating pipes. Since the requirements related to the overall heat transfer coefficients of the building envelope kept getting stricter in the last decades, external building elements (floor, ceiling, and even walls) are more and more preferred to be used for radiant heating. Obviously, this conception shows many advantages. The better thermal comfort sensation (large heating surfaces and low surface temperature) ought to be mentioned first. Secondly, the thermal barrier created around the heated spaces leads to a decrease in the heat demand. The increased heat losses of the system can be mentioned in the other pan of the balance sheet. In order to take an appropriate decision during the design process a complex energy analysis has to be carried out. CFD simulations provide reliable results, but in many cases, there is no time or there are no funds to finance the CFD analysis of a high number of scenarios. In this paper, a simplified method is presented which helps the stakeholders to take a rapid decision and to minimize the number of scenarios that should be analyzed with CFD. The presented method was validated by laboratory measurements in a test room placed in a climate chamber (the radiant heating system was an external wall built from solid brick).

Three scenarios have been analyzed in the case of a detached house:

- all external opaque building elements were used for radiant heating (1st scenario);

- the floor and the ceiling were used for radiant heating (2nd scenario);

- only the floor was taken into account for heating (3rd scenario).

Three different sets of requirements have been considered for the building envelope.

As a basic heating scenario "traditional" radiator heating was assumed. Meteorological parameters (outdoor temperature and solar radiation) have been determined based on five years (2009–2013) hourly measurement data.

It can be stated that increasing the number of external building elements involved as radiant heating surfaces, the total energy used for heating increases. The worst results have been obtained in the case of the nearly zero energy building when the energy used for heating increased by 23.2%–24.8% in comparison with the "traditional" radiator heating. Obviously, in absolute values, the increase in the energy use for heating was the highest in the 2002 and 2012 buildings. For nzeb's, from the total energy used for heating the share of heat losses may exceed the share of delivered heat. The lowest increase in the energy used for heating was obtained when only floor heating was assumed. In all analyzed cases, the floor temperature can be kept under the maximum allowable value given in comfort standards for buildings (the maximum value of the required floor surface temperature was 26.09 °C in the case of floor heating — 2002).

From the energy point of view, the utilization of radiant heating systems is more efficient if preponderantly the internal building elements would be used as heating surfaces. So, in the case of detached houses, it is more advantageous if the building has at least two levels and internal walls and slabs are used for radiant heating. The internal slab can be used for ceiling and floor heating simultaneously providing appropriate thermal comfort without the increase of heat losses of the heating system.

Limitations

In the case study, a detached house with certain geometry was taken into account. Thermo-physical parameters of the building have been established based on the requirements related to external building elements of residential buildings in Hungary

(2002, 2012, and 2022). For energy calculations, the hourly climate parameters measured in Debrecen (Hungary) were taken into account.

List of the used notations and abbreviations

nzeb's — nearly zero energy buildings;
RES — renewable energy sources;
REHVA — Federation of European Heating Ventilation and Air Conditioning Associations;
EPBD — energy performance of buildings directive;
WWR — windows to wall ratio, [%];
U_{wall} — overall heat transfer coefficient of external walls, [W/m^{2}K];
U_{slab} — overall heat transfer coefficient of the flat roof or slabs under unheated attics, [W/m^{2}K];
U_{window} — overall heat transfer coefficient of windows, [W/m^{2}K];
U_e — average overall heat transfer coefficient of the building envelope, [W/m^{2}K];
q — specific heat loss of the building, [W/m^{3}K];
K_{tr} — transmission heat loss coefficient of the building, [W/K];
A — is the area of an external building element, [m^2];
Ψ — is the linear heat transfer coefficient of a thermal bridge, [W/mK];
l — is the length of the thermal bridge, [m];
$\Sigma A/V$ — the ratio of building envelope area and heated volume, [m^2/m^3];
Q_{sd} — direct and indirect solar heat gains of the building, in [Wh];
Q_{sid} — indirect solar heat gains of the building, in [Wh];
H — heating degree day in [hK];
E_p — specific primary energy use, [kWh/m^{2}a];
δ — the thickness of the pipes covering layer, [m];
θ_w — the average over-temperature of the heating fluid, [K];
t_s — the supply temperature [°C];
t_r — the return temperature, [°C];
δ_{hl} — the thickness of the heating layer, [m];
λ — the heat conductivity of the material, [W/mK]
χ_i' — the partial heat transfer coefficient of internal layers covering the heating layer, [W/m^{2}K];
χ_e' — the partial heat transfer coefficient of external layers covering the heating layer, [W/m^{2}K];
h_e — the heat transmittance 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];
θ_m' — surface over-temperature (the temperature above the indoor air temperature, t_i) of the heating layer, [K];
θ_{mi}' — the mean inner surface over-temperature of the radiant building element, [K];
$\dot{q}_i$ — the specific heat released by the radiant building element to the room [W/m^2];
$\dot{q}_e$ — the specific heat losses, [W/m^2];
Q_{totd} — the daily energy needed for heating, [kWh];
A_j — the net area of the radiant external building element, [m^2];
Q_{tot} — the energy needed for heating in a heating season, [kWh];
x_1 — the number of starting day of the heating season;
x_2 — the number of ending day of the heating season;
N — the number of heating days in a heating season.
η_H — the heat gains utilization factor;
τ — is the room/building zone/building time constant, [s];
k and D — correlation coefficients;
COP — coefficient of performance of the air–water heat pump.

CRediT authorship contribution statement

Tünde Kalmár: Conceptualization, Data curation, Calculations, Investigation, Validation, Writing – original draft. **Béla Bodó:** Conceptualization, Experiments, Data curation, Calculations, Validation. **Ferenc Kalmár:** Conceptualization, Writing – review & editing.

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.

Data availability

The authors do not have permission to share data.

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Appendix

See Figs. A.1–A.8 and Tables A.1 and A.2.

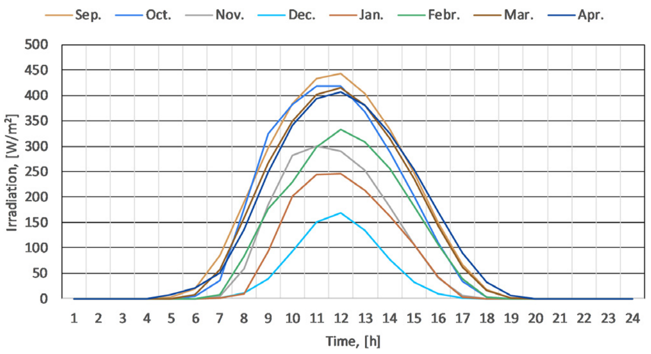

Fig. A.1. Irradiation on a south-oriented facade.

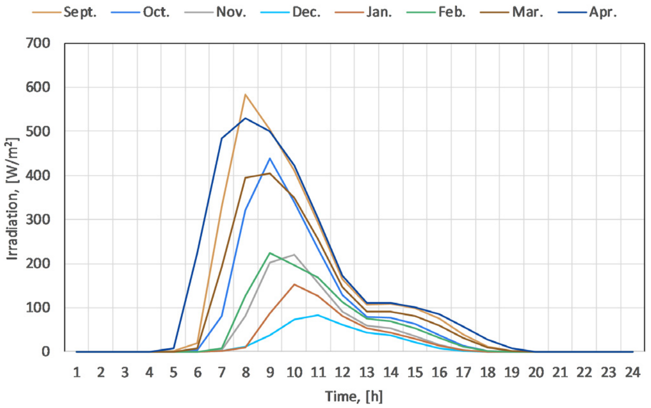

Fig. A.2. Irradiation on an east-oriented facade.

Table A.1
Mean required surface temperatures for radiant heating ($t_e = -15$ °C).

Analyzed case	Building element	2002	2012	2022
Floor-, wall- and ceiling heating	Floor	21.40	21.07	20.51
	Ceiling	22.11	21.61	20.77
	Wall	22.11	21.61	20.77
Floor- and ceiling heating	Floor	22.59	21.91	20.98
	Ceiling	23.89	22.86	21.48
Floor heating	Floor	26.09	24.50	22.35

Table A.2
Mean required warm water temperatures for radiant heating ($t_e = -15$ °C).

Analyzed case	Building element	2002	2012	2022
Floor-, wall- and ceiling heating	Floor	22.30	21.64	20.41
	Ceiling	21.85	21.34	20.36
	Wall	22.14	21.54	20.45
Floor- and ceiling heating	Floor	30.10	24.92	22.50
	Ceiling	25.46	25.98	23.04
Floor heating	Floor	35.61	31.38	25.87

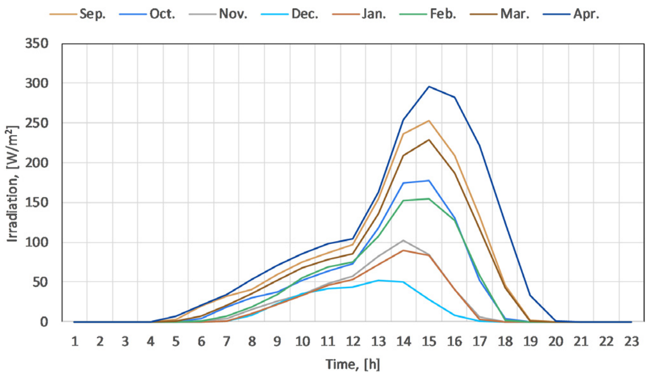

Fig. A.3. Irradiation on a west-oriented facade.

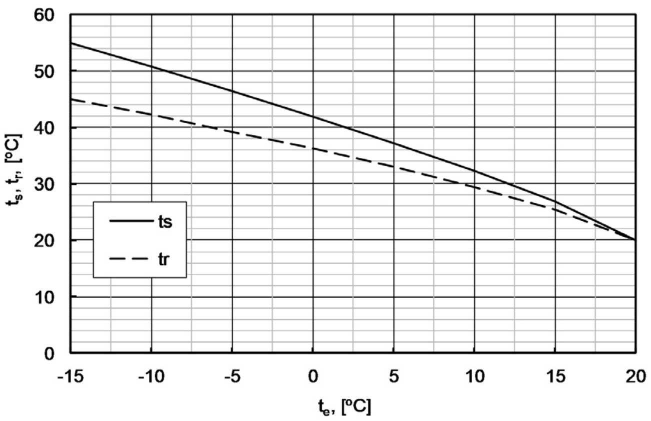

Fig. A.5. Supply and return temperature in the case of radiators.

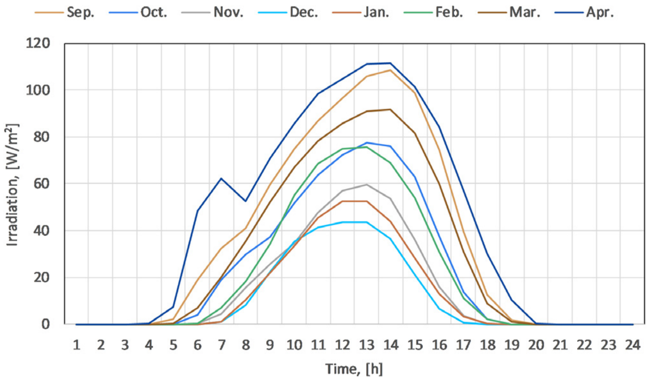

Fig. A.4. Irradiation on a north-oriented facade.

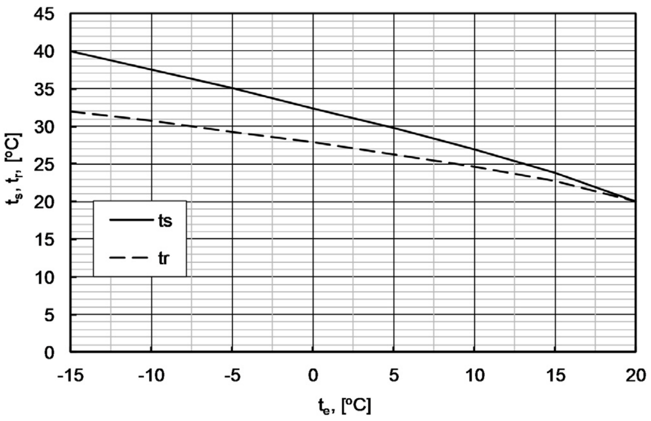

Fig. A.6. Supply and return temperature in the case of floor heating (2002).

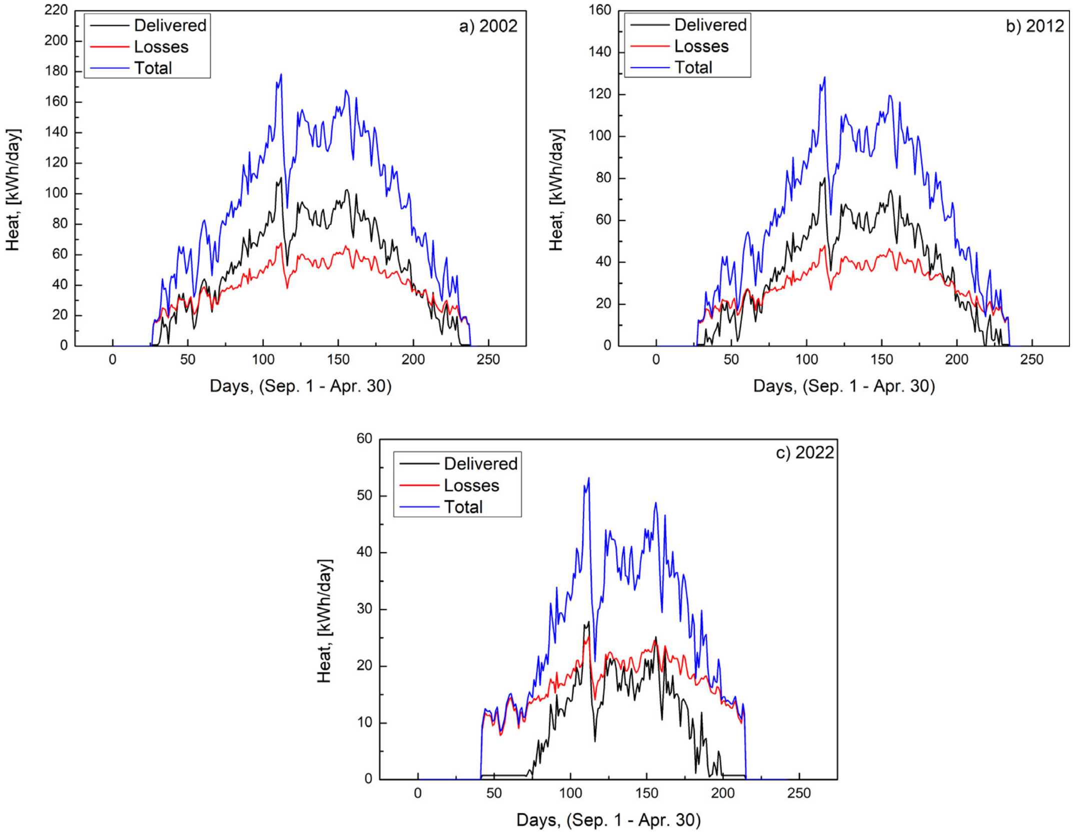

Fig. A.7. Daily energy demand for heating (floor and ceiling heating) (a) 2002; (b) 2012; (c) 2022.

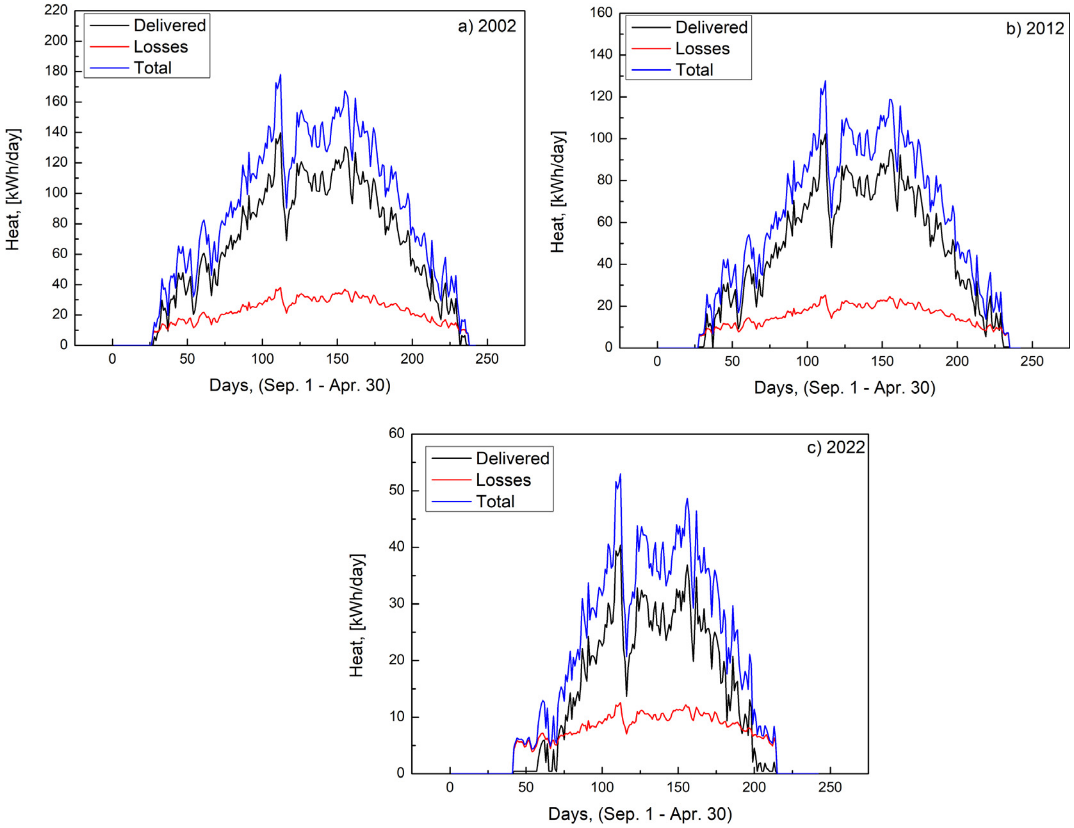

Fig. A.8. Daily energy demand for heating (floor heating) (a) 2002; (b) 2012; (c) 2022.

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