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- 24 g = CO₂ emission factor, kg/J
- 25 k = correction coefficient of the natural gas consumption
- 26 L = lifecycle, year
- 27 l = specific energy, J/kg
- 28 \dot{m} = mass flow rate of water, kg/s
- 29 m_1 = fixed monthly cost for metering, Euro
- 30 q = heat flux, W
- 31 R = primary energy consumption coefficient,
- 32 S = carbon dioxide emission, kg/year
- 33 T = temperature, K
- 34 U = coefficient of heat transfer, W/(m²K)
- 35 V = operating cost, Euro
- 36 δ = thickness, m
- 37 ε = efficiency of the heat transfer from the radiant wall panel to the air in the heated room,
- 38 ρ = density, kg/m³
- 39 **Subscripts and superscripts**
- 40 a = air,
- 41 a = average,
- 42 Emb = embodied,
- 43 el = electricity,
- 44 i = number of zone,

45 *in* = inlet,

46 *ng* = natural gas,

47 *o* = outside,

48 *sys* = system,

49 *TOT* = total,

50 *w* = water,

51 **Abbreviations**

52 PH-WOI = panel heating system without additional thermal insulation

53 PH-WI = panel heating system with additional thermal insulation

54 RH-WOI = radiator heating system without additional thermal insulation

55 RH-WI = radiator heating system with additional thermal insulation

56 **SHGC** = solar heat gain coefficient

57 **UFAD** = underfloor air distribution

58

59 **1. Introduction**

60 In Serbia, the concept of the radiant panel heating system (wall and floor panel) is relatively well-
61 known, but its application is still in its infancy. This is probably **as** a result of insufficient
62 information. However, the introduction of new materials, better control strategies, and better
63 utilization of alternative energy sources increase their demand and importance in the HVAC
64 industry. To prove the usefulness of such systems, it is necessary to compare these heating systems
65 with the classical heating systems regarding their energy, economy, and environmental influence.

66 In the literature, there are many papers dealing with investigations of the low temperature radiant
67 systems and their comparison with other heating systems regarding energy consumption and
68 obtained thermal comfort. Chen [1] compares the thermal comfort and the energy consumption
69 among a ceiling radiant heating system, a radiator heating system and a warm air heating system by
70 using airflow program Phoenics-84 and air-conditioning load program Accuracy. Haddad et al. [2]
71 compares the performance of a forced-air and a radiant floor residential heating system connected to
72 solar collectors. Raftery et al. [3] compares the performance of a joint underfloor air distribution
73 (UFAD) and radiant hydronic system with a typical only UFAD system. Imanari et al. [4] compares
74 a ceiling panel heating system in conjunction with an air-conditioning system and a conventional
75 air-conditioning system in term of thermal comfort, energy efficiency and cost efficiency. Stetiu [5]
76 shows that using a radiant cooling system instead of a traditional all-air system in office space could
77 save on average 30% of the energy consumption. Nobody compared the radiant wall heating
78 system with other heating systems in terms of energy, economy, and environmental influence.

79 The basic aim of this paper is to compare the radiant wall heating system with the radiator heating
80 system in terms of energy, economy, and environmental influence. During this research, the
81 operations of four heating systems are simulated such as: PH-WOI, PH-WI, RH-WOI, and RH-WI.
82 For one heating season, the consumption of natural gas for heating, the consumption of electricity
83 for heating, and the energy costs are analyzed as simulation results. In addition the carbon dioxide
84 emission is analyzed. When analyzing the energy consumption and the pollutant emission, the
85 embodied energy and the embodied CO₂ of additional thermal insulation are considered.
86 Furthermore, the investment into these systems is compared.

87

88 **2. Building**

89 **2.1 Building description**

90 An investigated residential building is shown in Fig.1. The building has two stories with 20 rooms;
91 18 of them are heated with the heating bodies located inside these rooms. The rooms that are not
92 heated are the storage room at the first floor designated as Pr 8 and the room at the second floor
93 designated as Sp 10. Other rooms are heated according the required temperature schedule [6]. **The**
94 **design temperature for indoor air in the living room, bedroom, and kitchen is 20 °C, and in the**
95 **hallway, and stairs 18 °C.**

96 It is assumed that this building is not surrounded by any other nearby buildings.

97 *<Fig.1 Isometric appearance of analyzed residential building with cuts for easier understanding of*
98 *distribution and appearance of rooms Here, Pr 1=hallway, Pr 2=stair, Pr 3=room, Pr 4=*
99 *bathroom, Pr 5=bedroom, Pr 6=living room, Pr 7=kitchen, Pr 8=storage, Pr 9=toilet, Pr 10=*
100 *bathroom, Sp 1=hallway, Sp 2=stair, Sp 3=bedroom, Sp 4=bathroom, Sp 5=toilet, Sp 6=working*
101 *room, Sp 7=living room, Sp 8=kitchen, Sp 9=bedroom, and Sp 10=passage.>*

102 **The total floor area of the building is 301 m². The gross external wall area is 306 m², and the gross**
103 **roof area is 187 m².** The external wall of the building consists of the thermal insulation (Styrofoam)
104 of 50mm thickness, the clay block (hollow brick) of 190mm thickness and the lime mortar of 20mm
105 thickness. The U-value of this wall is 0.57W/(m²K). **The total window glazing area is 27 m².** The
106 percentage of the glazing compared to the area of the overall external wall is 8.76%. The windows
107 are double glazed with U-value=2.72 W/(m²K), and SHGC=0.764.

108 **The building loses heat through its envelope by conduction, and by air infiltration at 0.5 air changes**
109 **per hour.**

110 The investigated building is used by two households with the total of 8 people. As electrical
111 consumers in the building, the classical electrical household devices are used (stoves, refrigerators,
112 TVs, radios, washing machines, freezers, and microwaves). In the building, the traditional hanging
113 lamps are used.

114

115 **2.2 Additional thermal insulation plate from wood wool**

116 To find better technical solution for application of radiant wall panel heating, it is necessary to use
117 some heat transfer barrier such as a thermal insulation plate. This heat barrier stops heat dissipation
118 from the radiant wall panel to the outdoors. However, it directs the heat to the heated room. These
119 plates represent the pressed mixture of long wood fibres and magnesite. As the final product, hard
120 and stable plates are obtained. The interior of these plates contains many air voids. Around 70% of
121 the plate volume presents the air voids that excellently **stop the heat transfer through the wall**.
122 Because of the air voids, these plates are also resistant to the negative influence of humidity. The
123 characteristic of these plates are given in Table 1.

124 *<Table 1.The characteristic of the thermal insulation plates from wood wool [7]>*

125 **3. Mathematical model**

126 **3.1 Used Software**

127 To simulate a thermal behaviour of the building and have accurate calculation results, software
128 EnergyPlus is used. This program is a very useful tool for modelling of energy and environmental
129 behaviour of buildings. **The program is initially developed by Lawrence Berkeley National**
130 **Laboratory, U.S. Army Construction Engineering Laboratory, and the University of Illinois [8].** In
131 the software, it is possible to input how people use building during its space heating. In this
132 direction, the complex schedules of heating can be defined together with the schedules for use of
133 lighting, internal energy devices and occupancy in the building. The influence of the solar radiation,
134 shadowing and infiltration is also taken into consideration [6, 9]. The investigated building and its
135 heating systems are modelled by using this software. Then, the general components of these
136 systems are modelled such as the boiler, pumps, convective baseboard heaters, and radiant wall
137 panel heaters.

138 **3.2 Heating systems**

139 The investigated heating systems operate in the building located in Belgrade, Serbia. They operate
140 by using hot water at different temperatures. The radiant wall panel heating operates with low water
141 temperatures. The classic non-condensing boilers used to generate heat, for all heating systems by
142 using natural gas. The boiler appears as electric consumers in the system. The parasitic electric load
143 from the boiler is consumed whenever the boiler is operating. The model assumes that this parasitic
144 power doesn't contribute to the heating of the water. Its load is about 75W when it operates. The
145 water circulation pump also uses electricity to operate. This is taken into account to calculate the
146 primary energy consumption.

147

148 3.2.1 Radiator heating system

149 A radiator heating system represents an installation of the central heating. In the system, heat is
150 generated in the boiler. For the generation of the heat, the natural gas boiler is used where the
151 chemical energy of natural gas is transferred into the heat. Then, the heat is distributed by hot water
152 (heat carrier) to the radiators. The radiators heat the rooms. The radiators are installed in each
153 heated room of the house. The hot-water is circulated by a water circulation pump, which operates
154 continuously. If the valves stop the hot-water flow, then this flow goes through the bypass pipe.
155 The radiators, as rule of thumb, are located next to the cold surfaces of the envelope. Then, they
156 significantly influence the thermal comfort. The radiators release the highest amount of heat to the
157 heated room by convection and one part by heat radiation [10]. To simplify the problem, the
158 radiator heating is modelled in EnergyPlus software by the convector model. EnergyPlus software
159 would define the size of the radiators based on the heat behaviour of the building. The equation of
160 heat flux between the radiator water and the room air is given as [6]:

$$161 \quad q = UA(T_{a,w} - T_{a,a}) \quad (1)$$

162 Here, $T_{a,w}$, $T_{a,a}$ stand for the mean temperatures of the radiator water and the room air, respectively,
163 UA stands for the product of the coefficient of heat transfer, and the heat transfer area.

164 In this system, $T_{a,w}$ is set at 70 °C. The inlet water temperature to the radiators is set at 80 °C.

165

166 3.2.2 Radiant wall panel heating systems

167 Radiant wall heating panels occupy large wall surfaces. In the investigated house, the heating panels
168 cover all external walls of the heated rooms - their surface area is the same as that of these walls
169 (212 m²). The heating panels are not used in the house floors and the house ceilings.

170 The radiant wall heating panels contain the inner pipes with the hot water. They may exchange up
171 to 70% of the heat with the heated room by thermal radiation [10]. Because of low temperature of
172 the heating panel and its hot water, the heat transfer rate from the heating surface is relatively small
173 to the heated room. This heating system consists of the radiant wall heating panels, the water
174 circulation pump, valves, and the natural gas boiler. The boiler operates with relatively low
175 temperature in the supply pipe and with small temperature difference between the supply water and
176 the return water. Through the entire heating system, the hot water is circulated by a water
177 circulation pump. The pump operates continuously and if valves stop the hot-water flow, then the
178 flow goes through the bypass pipe.

179 Because of high share of the radiation from the radiant wall panel heating system, a feeling of the
180 thermal comfort is obtained at much lower air temperature in the room than that by using other
181 heating systems.

182 The release of heat from the radiant wall panel depends on many factors such as the type of wall
183 covering, the mutual distance of pipes in the panel, the dimension of pipes, the structure of the wall,
184 and the type of radiant wall panel system.

185 EnergyPlus software is used for the simulation of the application of the radiant wall panel heating
186 systems as the software has all imbedded functions that are necessary for the successful simulation
187 of this application in buildings. The software uses the basic equation of heat balance for the internal
188 partitions (walls, ceilings, and floors), the envelope (walls, floors, and roofs) and the air in different

189 zones of the building. The transfer of heat through each of constructions is modelled by using the
190 conduction heat transfer functions [9]. The equation that defines the heat flux to/from the heating
191 panel [6]:

$$192 \quad q = \frac{T_{w,in} - C_3 - C_1 C_5}{\frac{1}{\varepsilon(m c_p)_{water}} + C_4 + C_2 C_5} \quad (2)$$

193

194 where $T_{w,in}$ stands for the inlet temperature of the hot water in the radiant wall heating panel, \dot{m}
195 stands for the mass flow rate of the hot water inside the radiant wall heating panel, c_p stands for the
196 specific heat capacity of the hot water, ε stands for the efficiency of the heat transfer from the
197 radiant wall heating panel to the air in the heated room, C_1 stands for the coefficient that includes
198 surface heat balance and past history terms as well as the influence of the current outside
199 temperature, C_2 stands for the coefficient that depends on the heat source transfer function term and
200 the coefficients of terms linked directly to the inside surface temperature, C_3 stands for the
201 coefficient that includes all of the history terms and the effect of the current outside temperature, C_4
202 stands for the heat source transfer function for the current time step, C_5 stands for the conduction
203 transfer function for the inside surface temperature at the current time step. **These coefficients and**
204 **other variables (the exit temperature of the hot water, and the external and internal temperature of**
205 **the wall surface) may be calculated by using equations given in [6].**

206 **In this system, the mean temperature of the hot water in the heating panels is set at 37 °C. The inlet**
207 **water temperature $T_{w,in}$ in the heating panels is set at 40 °C.**

208 **3.3 Weather**

209 The investigated building is located in Belgrade. Belgrade is a capital city of Serbia. Its average
210 height above the sea level is 132m. Its latitude is 44°48N, and longitude 20°28E. The city has a
211 moderate continental climate with distinct seasons (winter, spring, summer, and autumn). The
212 weather file used in the simulation is obtained by measurements at the Belgrade weather station
213 [11].

214 3.4 Total energy consumption of system

215 As the results, the simulations by EnergyPlus give the energy consumption from natural gas per
216 heating season (E_{ng}), and the energy consumption from electricity per heating season (E_{el}).

217

218 3.4.1 Primary energy consumption of heating system

219 The primary energy consumption per heating season at the investigated building is calculated by
220 using the following equation:

$$221 E_{sys} = E_{ng} + E_{el}R \quad (3)$$

222 Here, R stands for the primary energy consumption coefficient. This coefficient is defined as the
223 ratio of the total input energy of energy resources (hydro, coal, oil and natural gas) and the finally
224 generated electric energy. For the Serbian energy mix for electricity production, $R = 3.61$ [12].

225 3.4.2 Embodied energy

226 The embodied energy is defined as the commercial energy (fossil fuels, nuclear, etc) that was used
227 in the work to make any product. The embodied energy consumption per heating season for the
228 investigated building is calculated by using the following equation:

$$229 E_{Emb} = \frac{l_{Emb} \cdot \rho \cdot \delta \cdot A}{L} \quad (4)$$

230 Here, l_{Emb} stands for the specific embodied energy of the additional thermal insulation plate, ρ
231 stands for the specific density of the additional thermal insulation plate, δ stands for the thickness of
232 the additional thermal insulation plate, A stands for the application area of the additional thermal
233 insulation plate, and L stands for the lifecycle of the heating system. **The lifecycle of each heating**
234 **system is set at 20 years [10].** For the additional thermal insulation plate, its geometrical
235 characteristics, and the values of embodied energy are given in Table 1.

236

237 **3.4.3 The total energy consumption of the system**

238 The total energy consumption of the system is the sum of the primary energy consumption by the
239 heating system and the embodied energy of the additional thermal insulation panel. It is given by
240 the following equation:

$$241 \quad E_{TOT} = E_{sys} + E_{Emb}. \quad (5)$$

242 **3.5 Total operating cost**

243 The total operating cost to run the heating system is calculated by using the following equation

$$244 \quad V_{TOT} = f_{el}E_{el} + f_{ng}E_{ng}k m_1. \quad (9)$$

245 Here, f_{el} stands for the specific cost of the consumption of electricity, f_{ng} stands for the specific
246 cost of consumption of natural gas with the energy value of 33338 kJ/m³, k stands for the correction
247 coefficient of the natural gas consumption $k=1.068$ [13], m_1 stands for the fixed monthly cost for
248 gas metering [13]. In this equation, the fixed monthly cost for electricity metering is not included
249 because this cost is not significant. These cost factors are given in Table 2.

250 *<Table 2.The price of energy in Serbia in May 2011 [14,15]>*

251 **3.6 Carbon dioxide emission**

252 **3.6.1 Carbon dioxide emission of heating system**

253 The carbon dioxide emission of the heating system during its operation is calculated by using the
254 following equation:

$$255 \quad S_{sys} = g_{ng}E_{ng} + g_{el}E_{el}. \quad (10)$$

256 Here, g_{ng} stands for the specific CO₂ emission factor for natural gas (kg CO₂/GJ), g_{el} stands for the
257 specific CO₂ emission factor for electricity (kg CO₂/GJ). The emission factors are given in Table 3.

258 *<Table 3.The CO₂ emission factors for the electric energy and natural gas [7]>*

259 **3.6.2 Embodied CO₂ emission of additional thermal insulation plate**

260 The embodied CO₂ emission of the additional thermal insulation plate is calculated by using the
261 following equation:

$$262 \quad S_{Emb} = \frac{g_{Emb} \cdot \rho \cdot \delta \cdot A}{L} . \quad (11)$$

263 Here, g_{Emb} stands for the specific embodied CO₂ emission factor of the additional thermal
264 insulation plate. **The emission factors are given in Table 1.**

265

266 **3.6.3 Total CO₂ emission of the system**

267 The total CO₂ emission of the investigated heating system is the sum of the CO₂ emission of the
268 heating system and the embodied CO₂ emission of the additional thermal insulation plate. It is
269 represented by the following equation:

$$270 \quad S_{TOT} = S_{sys} + S_{Emb} . \quad (12)$$

271 **4. Results and discussion**

272 In these investigations, the four heating systems: the RH-WOI (the traditional system often used in
273 households in Serbia), the RH-WI, the PH-WOI, and the PH-WI are simulated during their
274 operation at the heating season. In entire Serbia, the heating season starts at 15 October and ends at
275 15 April next year.

276 **4.1.1 Results**

277 The simulation gives the results for the energy consumption, operating costs, and CO₂ emission for
278 each of all four heating systems installed in the investigated building.

279 In Fig.2, the consumptions of natural gas energy, electrical energy, primary energy, and total energy
280 are given for each heating system per heating season.

281 <Fig. 2 Energy consumption per heating season.>

282 As the electricity consumption is very small to be seen in Fig 2, it is shown in Fig 3.

283 <Fig. 3 Electric consumption of water circulation pump per heating season.>

284 Figure 4 shows the effect of additional thermal insulation to the energy consumption for different
285 heating systems.

286 <Fig. 4 Effect of additional thermal insulation to the energy consumption
287 for different heating systems: a) Radiator heating system, b) Panel heating system>

288 Figure 5 shows the effect of heating system to the energy consumption.

289 <Fig. 5 Effect of heating system to the energy consumption for different walls:
290 a) without additional thermal insulation, b) with additional thermal insulation>

291 Figure 6. shows the nominal power of the boilers serving the investigated building for each heating
292 system.

293 Fig. 6 Nominal power of boiler.>

294 The investment in € in each heating system is shown in Table 4.

295 <Table 4. Investments in investigated systems, prices in Euros (€) [16,17]>

296 In Fig.7, the operating costs are shown for each simulated heating system. The figure also gives the
297 total operating cost during the heat season, which includes the costs for electricity and natural gas
298 for heating.

299 <Fig. 7. Operating cost of heating per heating season.>

300 The yearly CO₂ emissions are shown for each heating system in Fig. 8. The figure takes into
301 account that the emission factors for Serbia are $g_{el} = 206.53$ kg/GJ, and $g_{ng} = 56.1$ kg/GJ.

302 <Fig. 8 CO₂ emission per heating season.>

303 **4.1.2 Discussion**

304 By using all presented results in Figs. 2 to 8, the energy, cost, and CO₂ emission are analyzed,
305 discussed, and compared for the radiant wall heating panel systems and radiator systems. From
306 Fig.2, it may be found that the consumption of the natural gas for space heating is the lowest for the
307 PH-WI ($E_{ng}=40.54$ GJ/year) and the highest for RH-WOI ($E_{ng}=66.18$ GJ/year) that makes their
308 difference of 39%. From Fig.3, the electrical consumption is the lowest for the PH-WI ($E_{el}=0.14$
309 GJ/year) and the highest for RH-WOI ($E_{el}=0.23$ GJ/year) that makes their difference of 40%. From
310 Fig.2, the primary energy consumption for space heating is the lowest for the PH-WI ($E_{sys}=40.96$
311 GJ/year) and the highest for RH-WOI ($E_{sys}=66.88$ GJ/year). Then, the relative difference in E_{sys}
312 between PH-WI and RH-WOI is 39%. Also, the total energy consumption for space heating is the
313 lowest for the PH-WI ($E_{TOT}=45.03$ GJ/year) and the highest for RH-WOI ($E_{TOT}=66.88$ GJ/year).
314 Then, the relative difference in E_{TOT} between PH-WI and RH-WOI is 33%. It can be seen the
315 relative difference in E_{TOT} between PH-WI and RH-WOI is lower than the relative difference in E_{sys}
316 between PH-WI and RH-WOI by 6%. Note that $E_{TOT} = E_{sys} + E_{Emb}$.

317 Regarding sensitivity to additional thermal insulation, Fig. 4 shows that the panel heating systems
318 are more sensitive to application of additional thermal insulation than the radiator heating systems.
319 With application of the additional thermal insulation in the house with the heating panel systems,
320 the primary energy consumption by the heating panel systems is reduced by 22% and the total
321 energy consumption (when the embodied energy is taken into account) by 14%. Then, the primary
322 energy consumption by the radiator systems is reduced by 15% and the total energy consumption by
323 8%.

324 Regarding sensitivity to the used heating system, Fig.5 shows that the radiator heating system
325 consumes more primary energy than the panel heating systems. For the house without additional
326 thermal insulation, the radiator heating system consumes 21% more primary energy than the panel
327 heating systems. Furthermore, for the house with additional thermal insulation, the radiator heating
328 system consumes 28% more primary energy than the panel heating systems, and 26% more total

329 energy (when the embodied energy into thermal insulation is taken into account) than the panel
330 heating system.

331 From Fig.6, the nominal power of the boiler is the lowest for the PH-WI ($Q_n=24.9$ kW), and the
332 highest for RH-WOI ($Q_n=27.6$ kW). The relative difference in the nominal power of the boiler
333 between RH-WOI and PH-WI is 10%.

334 From Fig.7, the cost of the primary energy for space heating is the lowest for the PH-WI
335 ($V_{TOT}=1.76$ €/m²), and the highest for RH-WOI ($V_{TOT}=2.84$ €/m²), that makes their difference of
336 38%. Also, Table 4 shows that the most expensive system is the PH-WI (15079 €), and the most
337 inexpensive system is the RH-WOI (4369 €). The investment in the PH-WI is about 3 times higher
338 than that in the RH-WOI.

339 From Fig.8, the CO₂ emission of the heating systems due to use of energy for the space heating is
340 the lowest for the PH-WI ($S_{sys} = 2.30$ tCO₂/year) and the highest for RH-WOI ($S_{sys} = 3.76$
341 tCO₂/year), that makes their difference of 39%. The total CO₂ emission is the lowest for the PH-WI
342 ($S_{TOT} = 2.50$ tCO₂/year), and the highest for RH-WOI ($S_{TOT} = 3.76$ tCO₂/year) that makes their
343 difference of 33%.

344 Finally, this investigation of the four heating systems points out that in Serbia the PH-WI is the
345 most energy efficient, and has the lowest negative impact on the environment. However, the PH-WI
346 is the most expensive. This analysis is done with natural gas as an energy source and refers to only
347 the space heating. In the future, an analysis may be done for space heating and cooling by using
348 low-temperature sources with heat pump [18].

349 **Conclusion**

350 This paper reports the results of investigations of performances of the four heating systems: RH-
351 WOI, PH-WOI, PH-WI, and RH-WOI. These heating systems operate in the residential house in
352 Belgrade, Serbia. Additionally, this study takes into account the embodied energy and embodied

353 CO₂ of the additional thermal insulation of the external building wall. The operation of heating
354 systems is evaluated by analysing their energy consumption, cost, and CO₂ emission.

355 Regarding sensitivity to additional thermal insulation, the panel heating systems are more sensitive
356 to application of additional thermal insulation than the radiator heating systems. Regarding
357 sensitivity to the used heating system, the radiator heating system consumes more primary energy
358 than the panel heating systems. It is found that the PH-WI has the smallest total consumption of
359 energy, and the smallest impact to environment. However, the economic analysis shows that the
360 PH-WI has the smallest cost of space heating but is the most expensive in terms of investment. The
361 additional thermal insulation prevents a significant thermal conduction loss to the outdoors. This
362 impact of the additional thermal insulation is much higher with the panel heating systems than with
363 radiator systems. The embodied energy and embodied CO₂ of additional thermal insulation does not
364 have significant adverse impact on heating systems.

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