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EXERGY METRICATION OF LOW TEMPERATURE PANEL HEATING SYSTEMS

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Abstract: *This paper compares the exergy efficiency of panel heating system using different energy sources such as natural gas and geothermal heat pump. The analysis is performed on a CAD model of the family building, located in Kragujevac, Serbia with different heating systems such as floor panels, wall panels, ceiling panels and floor-ceiling panels. The operation of these panels is simulated by software EnergyPlus, product of Lawrence Berkley Laboratory in USA. This research is a part of the project "Development of a net-zero-energy building".*

Key words: *exergy efficiency, radiant panel, heat pump, energy consumption, EnergyPlus, ground heat source.*

1. INTRODUCTION

Nowadays, the panel heating systems are increasingly used in Serbia due to accessible price of panels. Since panel heating systems work with low-temperature of fluids, it is important to select the proper heating generator. Thus, the classic gas boilers remain the choice due to a low investment rates. On the other hand, experts from the field will strongly recommend a Ground Source Heat Pumps (GSHP) system.

To better understand the effectiveness of the panel heating systems in addition to the analysis of energy flow, the analysis of exergy flow must be also included. Exergy analysis is an important tool in designing the efficiency of the thermal systems and in determining of the unavoidable thermal inefficiencies of the system [1].

Exergy GSHP devices and applications are widely described and tested in literature. In [2], a relatively new approach of ground heat exchanger (GHE) optimization is presented, based on the second law of thermodynamics. It was adopted to test an optimum combination of circulating water flow rate and pipe diameter. Other authors [3] analyzed an energy and exergy flow of a ground-coupled heat pump (GCHP) system. The exergy flows between the components and the consumptions in each of the GCHP system components were determined. In [4], the authors compared different heat generators and energy and exergy analyses. They concluded that the ground source heat pump heating system is better than air source heat pump or conventional heating system. Thermodynamic analysis of a GSHP system for district heating in terms of both energy and exergy analysis, described in [5], aims to improving the process efficiency. The on-going climatic change and effects of global warming with significant impact on GSHP systems are investigated in [6].

Some studies are conducted to investigation of panel systems performance in different heating objects inside the building. Paper [7] showed that optimal operation of radiant panels with ground-source heat pumps driven by renewable energy sources improves the exergy efficiency and primary energy ratio. In [8], the authors applied the low-temperature radiant systems in combination with localized automated ventilation in a museum in Ljubljana, Slovenia. Using this solution the demand for energy was reduced for heating and cooling by 60.5%. In [9, 10], the wall heating system and radiators connected on noncondensing natural gas boiler were compared. Authors analyzed different panel heating system (floor, wall, ceiling and floor-ceiling) connected on a natural gas boiler.

In this paper, the exergy analysis showed benefits of using low-temperature sources in panel systems. We tested natural gas boiler as a high-temperature source and GSHP as a low-temperature.

As a panel system, we tested floor heating, wall heating, ceiling heating and newly developed concept of floor-ceiling heating system [10].

2. MATHEMATICAL MODEL

2.1 Building description

The analyzed building is a residential family house (Figure 1). The building is designed for one family and has a living area of $190m^2$. The envelope of the building is made of 190 mm porous brick, 50 mm thermal insulating layer and 20 mm lime mortar. The U-value is 0,57W/ (m^2K). The windows are double glazed with U-value of 2.72 W/ (m^2K). The overall ratio of glass to the exterior walls is 7.32%, where the total area of exterior walls is $264m^2$ and the whole area of windows is $19m^2$.

2.2 CAD model of the building

The simplified CAD model of the building and its ground level is created in SketchUp 3D modeling software (Trimble Navigation). The CAD models of the building has one living room, hallway, bathroom and three bedrooms.

The analyzed building is located in Kragujevac, Central Serbia. The elevation of Kragujevac is 209m and its latitude and longitude are 44^{o}N and 20^{o}55E. The city has a continental temperate climate with four different seasons (summer, autumn, winter and spring). As part of the EnergyPlus, weather file used as an *.epw file generated by the Meteonorm [11]. The heating season runs in Kragujevac from 15 October to 15 April [12].

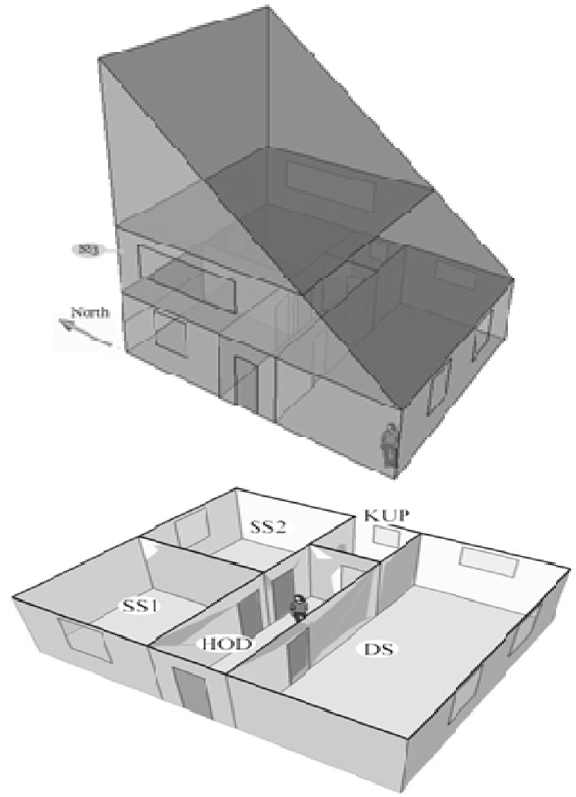


Fig. 1. Analyzed building – CAD models: DS – living room, HOD – hallway, KUP – bathroom, SS1 – bedroom, SS2 – bedroom, SS3 – bedroom.

2.3 Description of the heating systems

In order to calculate the primary energy consumption, as a heating systems in this model we selected heating panels and heat generator. In this approach, we investigated: 1. the floor heating, 2. the wall panel heating, 3. the ceiling heating and 4. the floor-ceiling heating. The floor heating panel had the total surface area of $190m^2$. The wall heating panel is located at the external wall and its total surface area is $210m^2$. The ceiling heating panel is located at the ceiling of the first and second store of the building and its total surface area is $190m^2$. The floor-ceiling heating panel operates as a ceiling heating of the lower store and as a floor heating of the upper store. Its total surface area is $95m^2$.

The main heating source of the heating panels is the water with the same temperature of 37^{o}C for all heating systems, circulated by the electric pumps.

As a heat generator, we used natural gas boiler and ground source heat pump (GSHP). For all four heating panels the power of natural gas boiler was 24kW. The nominal electricity input of GSHP was 4kW. Also, length of geothermal probe was 76m with two U-pipes.

2.4 Primary energy consumption of the heating system

The primary energy consumption per heating season of the analyzed building is calculated by the following equations:

$$E_{sys} = E_{ng} + R\,E_{el} \quad (1)$$
$$E_{sys} = R\,E_{el} \quad (2)$$

Equation (1) refers to the system with a natural gas boiler and the equation (2) refers to the heating system with GSHP unit.

Here, E_{ng} represents the consumption of natural gas per heating season, E_{el} represents the consumption of electricity per heating season and R stands for the primary energy consumption coefficient. This coefficient is defined as a ratio of the total input energy of energy resources (hydro, coal, oil and natural gas) and the finally produced electric energy. Its value for the Serbian energy mix for electrical energy production is $R = 3.01$ [13].

2.5 Consumed exergy

The exergy consumed by the analyzed heating panels is calculated by:

$$Ex_{cons} = \sum_{i}^{n} Ex_{cons_i} = \sum_{1}^{n=6}\left(1 - \frac{T_o}{\left(\frac{T_{in_i} - T_{ret_i}}{2}\right)}\right)E_{h,t} \quad (3)$$

where, n is the number of heating rooms, T_o is the reference temperature, T_{ini} and T_{reti} are the inlet and return temperatures of heating emission panels in the observed room and $E_{h,t}$ - transferred heat from the panels.

2.6 Lost exergy

The lost exergy presents exergy supplied by natural gas to the boiler through combustion. This is calculated using the following equation:

$$Ex_{dest} = (1 - T_o/T_f)E_{h,s} \quad (4)$$

where, T_f is the temperature of heat source, (combustion temperature for natural gas, T_f = 2000K [7], average fluid temperature from ground exchanger T_f = 283.03K) and $E_{h,s}$ – transferred energy from heat source.

2.7 Exergy efficiency of heat transfer

A value of exergy efficiency of heat transfer between the boiler and the heating panels is calculated by using the following equation:

$$\Psi_R = Ex_{dest}/Ex_{sup}. \quad (5)$$

3. RESULTS AND DISCUSSION

For a better understanding of the flow exergy, on the figure 2 and 3 the final and primary energy consumption are represented. Comparing the used panel systems, on Fig. 2, floor-ceiling heating has the lowest consumption of final energy. The consumption of the floor-ceiling panels connected with natural gas boiler and GSHP was 48kWh/m^{2}a and 20kWh/m^{2}a, respectively.

The classical ceiling heating has the highest consumption of final energy 104kWh/m^{2}a and 45kWh/m^{2}a for natural gas boiler and GSHP, respectively.

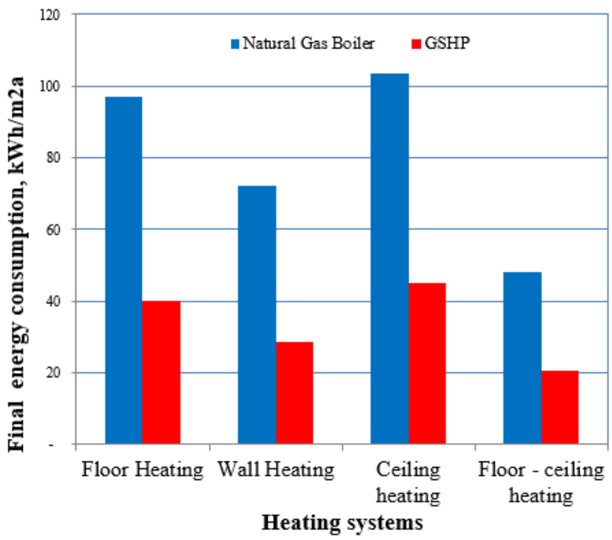


Fig. 2. The final energy consumption of heating panel system connected on natural gas boiler and GSHP

Figure 3 clearly shows the primary energy consumption of the four observed panel heating systems with the same ratio of primary energy consumption among the four analyzed panel heating systems.

However, as a result of higher primary energy conversion factors for electricity from National grid, primary energy consumption of panel heating systems connected to the heat pump will be higher than the panel heating systems connected to the natural gas boiler.

The final energy of the floor-ceiling panel heating system showed the least consuming of energy, 54kWh/m^{2}a for the system connected to the natural gas boiler and 63kWh/m^{2}a for the floor-ceiling heating system connected with GSHP.

Also, classic ceiling heating consumes the most energy 115kWh/m^{2}a for system connected to the natural gas boiler and 137kWh/m^{2}a for the system connected to the GSHP.

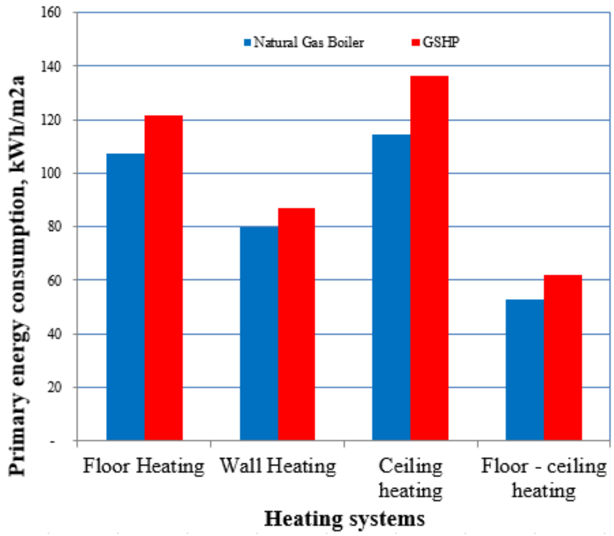


Fig. 3. The primary energy consumption of heating panel system connected on natural gas boiler and GSHP

Proportional to the energy consumption among comparison panels there is a relation in exergy consumption.

Figure 4 shows the exergy consumption of four observed panel heating systems. The floor-ceiling panel has the lowest exergy consumption, 0.69GJ for the system connected to the natural gas boiler and 0.73GJ for the system connected to the GSHP. Also, the classic ceiling heating system has the highest exergy consumption and it is 5.1GJ for the system connected to the natural gas boiler and 1.8GJ for the system connected to the GSHP.

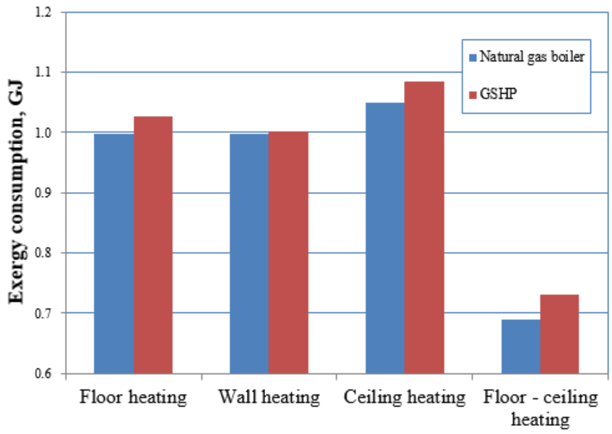


Fig. 4. The exergy consumption of heating panel system connected on natural gas boiler and GSHP

Figure 5 illustrates the amount of exergy lost in the gas boiler and GSHP. This is due to more exergy lost during combustion of natural gas in the boiler than for operation of the GSHP. This means, the floor-ceiling panels lost the least exergy, 5.81GJ for the system connected to the natural gas boiler and 0.09GJ for the system connected to the GSHP. Also, the most exergy is lost at the classic ceiling panels, 12.68GJ for the system connected to the natural gas boiler and 0.11 GJ for the system connected to the GSHP.

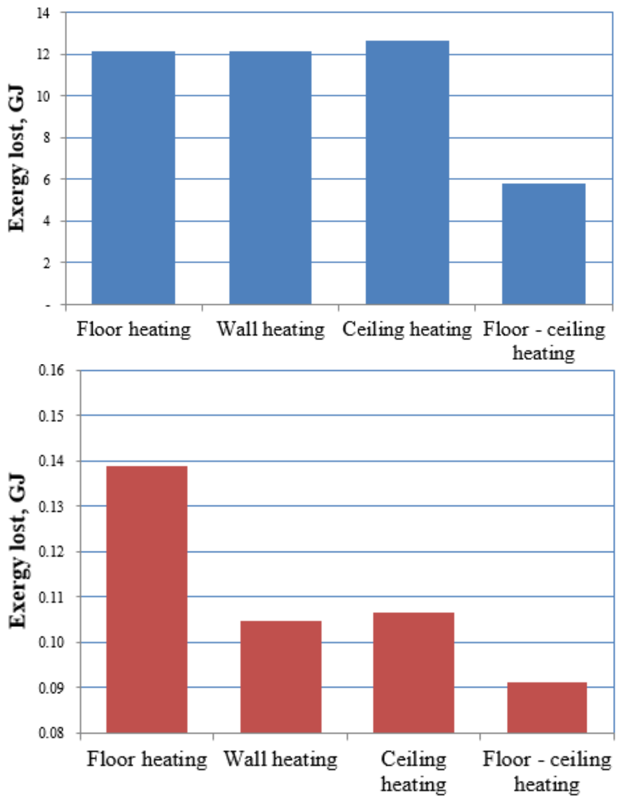
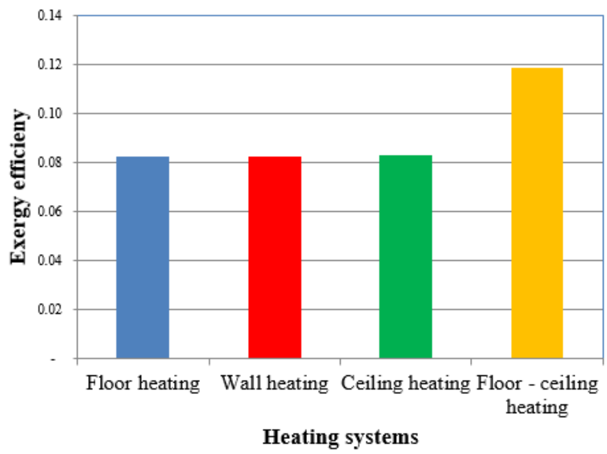


Fig. 5. The exergy lost of heating panel system connected on natural gas boiler (above) or GSHP (below)

Figure 6 illustrates the exergy efficiency of panel heating systems connected to the boiler or a GSHP. The exergy efficiency actually poses a mismatch between consumed and lost exergy. Less disagreement will provide higher efficiency and vice versa. As with combustion of natural gas in the boiler spent much more the amount of exergy than the GSHP the level of exergy efficiency will be much lower for panel system equipped with natural gas boiler. In panel systems connected to the natural gas boiler the floor-ceiling heating is the most exergy effective 0.0118 while the other three systems has approximately the same efficiency of about 0.082.

Panel systems connected to the GSHP suggests that exergy efficiency values are much higher, 10.16 for classic ceiling heating, 8.02 to floor-ceiling heating, 7.38 for floor heating and 9.56 for the wall heating. This is due to the smaller differences between consumed and lost exergy.



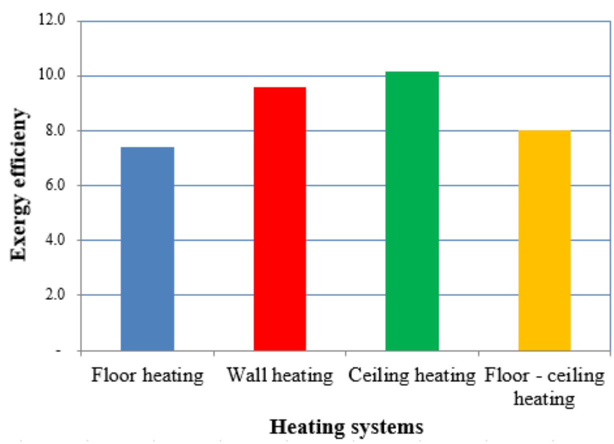


Fig. 6. The exergy efficiency of heating panel system connected on natural gas boiler (above) or GSHP (below)

4. CONCLUSION

In this paper, the exergy analysis of panel heating systems is presented. As a panel heating systems we used the floor heating, wall heating, ceiling heating and floor-ceiling heating. As a heat generators two most commonly used devices are selected: the natural gas boiler and the geothermal heat pump. To compare the wasted energy of panel systems the floor-ceiling panels has the minimum requirements for the amount of energy, while the classic ceiling panels have the highest requirements. Also, the same ratio holds for the required amount of exergy.

If it compares the heat sources, the gas boilers use more final energy then the GSHP. However, due the high transformation factor of primary energy from the power grid, the GSHP require more primary energy.

When considering exergy consumption of analyzed panel heating systems, the exergy consumption is slightly higher for the panel systems connected to the GSHP. However, drastic differences occur in quantity exergy that is lost in generating heat. It is much higher for the panel systems connected to the natural gas boiler. This is due to the high temperature combustion of natural gas. In addition, the level of exergy efficiency is much higher for the panel systems connected to the GSHP $\Psi = 7.38$ to 10.16.

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Măsurarea exergiei sistemelor de încălzire cu panouri la temperatură joasă

Rezumat: Lucrarea își propune să compare eficiența exergiei unui sistem de încălzire cu panouri folosind diferite surse de energie. Gazele naturale și pompele de căldură geotermale sunt utilizate ca surse de energie. Diferite tipuri de panouri, de pardoseală, de perete, de tavan și de podea sunt folosite ca sisteme de încălzire. Casa care a fost analizată în acest studiu este situată în Kragujevac, Serbia, iar cercetarea este parte a proiectului "Development of a net-zero-energy house". Funcționarea acestor panouri este simulată prin software-ul EnergyPlus, produs de Lawrence Berkley Laboratory din SUA.

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