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RESEARCH ARTICLE

Optimizing Home Heating: A Numerical Approach to Assessing Radiator, Floor, and Ceiling Heaters

HANA CHARVÁTOVÁ[1], ALEŠ PROCHÁZKA[2,3], (Life Senior Member, IEEE), MARTIN ZÁLEŠÁK[1], AND VLADIMÍR MAŘÍK[3], (Life Fellow, IEEE)

[1]Faculty of Applied Informatics, Tomas Bata University in Zlín, 760 01 Zlín, Czech Republic
[2]Department of Mathematics, Informatics and Cybernetics, University of Chemistry and Technology at Prague, 160 00 Prague, Czech Republic
[3]Czech Institute of Informatics, Robotics and Cybernetics, Czech Technical University in Prague, 160 00 Prague, Czech Republic

Corresponding author: Hana Charvátová (charvatova@utb.cz)

ABSTRACT The paper presents a numerical assessment of various room heating methods using assembled room models. It compares the efficiency of floor heating, ceiling heating, and plane radiator heating in a selected room of a family house under winter conditions in the Central European climate zone. COMSOL Multiphysics software is used for computer simulations, and the output data are subsequently processed and analyzed using MATLAB software. Results indicate that floor and ceiling heating systems achieve higher and more rapid temperature increases compared to plane radiators. The distribution of air temperature within the room is also analyzed, revealing that floor heating provides the most uniform temperature distribution. These findings contribute to the development of effective heating strategies for residential buildings in similar climatic conditions. Furthermore, appropriate processing of output data obtained from computer simulations using artificial intelligence tools enhances the accuracy and efficiency of numerical analysis methods.

INDEX TERMS Numerical simulation, heat transfer, floor heating, ceiling heating, plane radiator, thermal insulation, thermal comfort, artificial intelligence.

I. INTRODUCTION

A wide range of heating systems are used to heat residential buildings. They include plane radiators, floor and ceiling heating systems, and other devices. Each of these heating methods has both advantages and disadvantages, which are related to different principles of heat transfer, with different energy sources, efficiency, and costs. The principle of heat transfer by heating with a plane radiator is mainly convection, where heat is transferred by air circulation. This method of heating is often used due to its simplicity and speed in heating a room, but it can cause uneven temperature distribution. Heat transfer in floor heating is a combination of convection and radiation. Heat is transferred from the floor to the room, ensuring even temperature distribution and higher comfort for users. Floor heating is popular for its ability to maintain a pleasant temperature at lower operating temperatures but can be more challenging to install. Heat transfer in ceiling heating also involves a combination of convection and radiation. Heat is transferred from the ceiling down into the room, which can be advantageous in spaces with high ceilings.

Numerous studies have focused on comparing different heating methods in terms of their efficiency and achieving the desired thermal comfort. The authors of [1] compared space heating energy consumption using different methods and analyzed potential energy savings. The authors of [2] focused on energy-saving mechanisms for heating and cooling buildings and compared different methods based on temperature differences. Study [3] aimed at comparing thermal comfort and energy saving under eight different heating methods. The thermal performance of six different radiant systems, including floor and ceiling heating, was analyzed in paper [4]. The authors of [5] investigated a baseboard heater, convector, and radiant heater under equal thermal comfort conditions in a bi-climatic chamber at various cold room temperatures. The study focused on how heat distribution affects the effectiveness of each heating system. The findings suggested that the type of heater and its heat distribution significantly influence the heating system's thermal comfort and energy efficiency.

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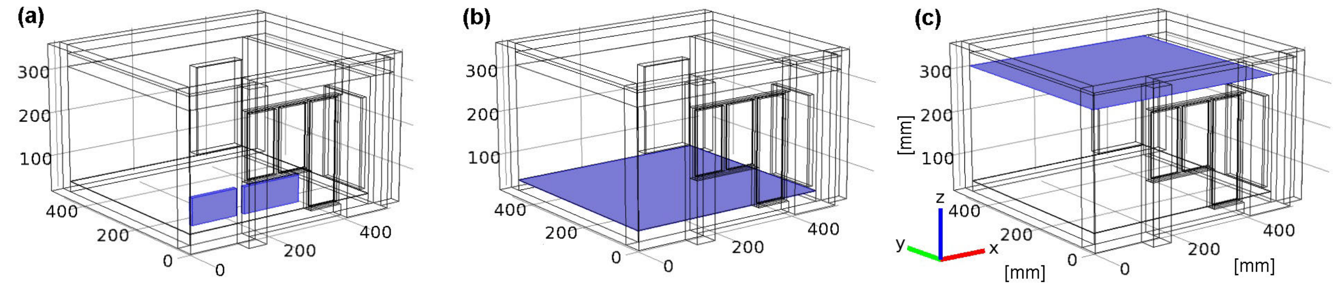

FIGURE 1. Geometry of the models: (a) a room heated by plane heaters, (b) a room with floor heating, (c) a room with ceiling heating. Blue colors indicate heating surfaces.

From the perspective of efficiency, an important factor is the appropriate design of the heating device considering the construction of the building itself and the climatic conditions of the location where the building is situated. Ceiling heating is very versatile and can be used in a wide range of buildings. Floor heating is suitable for various types of buildings but is best suited for well-insulated new buildings and buildings with low energy consumption.

This paper compares ceiling and floor heating using an electric heating foil. The advantage of using electric heating foil for floor and ceiling heating is the ease of installation and the ability to control the temperature precisely. Electric heating foils are flexible and can be used for both floor and ceiling heating. On the other hand, a disadvantage may be higher operating costs compared to other heating methods.

An installation process of electric floor foil includes preparing the substrate, laying the foil, and connecting it to the electrical system. The installation process of electric ceiling foil is similar to that of floor foil, with the difference that the foil is installed on the ceiling.

In both of the above-described processes, the heat transfer is supported by the installation of thermal insulation. The impact of floor thermal insulation in floor heating is necessary to minimize heat loss and ensure efficient heat transfer into the room [6]. The effect of ceiling insulation on ceiling heating is similar to that of floor heating. Ceiling insulation ensures that heat is efficiently transferred into the room and minimizes heat loss. For example, extruded polystyrene, polyurethane boards, and reflective polyethylene films are used for thermal insulation of the floor heating foil. Mineral wool, glass wool, polyurethane foam, etc., are used as ceiling thermal insulations.

An optimal air temperature in the room in winter is essential for ensuring thermal comfort. The recommended temperature is between 20-22°C, which ensures a pleasant environment without unnecessary energy losses. The maximum suitable surface temperature for ceiling heating should not exceed 35°C to avoid overheating the room and provide even temperature distribution. The maximum suitable surface temperature for floor heating should be around 29°C.

Experimental assessment of the thermal behavior of buildings is time-consuming, economical, and technically demanding. Therefore, numerical calculation methods [7], [8], [9], [10], [11], [12], [13], [14], [15] or a combination of both mentioned methods are used for this purpose [16], [17], [18], [19], [20], [21].

In addition, numerical computational methods can be combined with rapidly developing artificial intelligence tools [22], [23], which have a number of advantages. From the point of view of optimizing monitored home heating models, artificial intelligence (AI) can optimize home heating models. AI models can adjust heating patterns based on real-time sensor data, such as room temperature, humidity, and occupancy levels, to improve energy efficiency and maintain comfort. For radiators, AI can optimize the heat distribution by predicting the thermal dynamics of the room and adjusting flow rates in real time. In floor heating systems, AI can predict heat storage capacity and adjust heating schedules, especially when coupled with renewable energy sources like solar power. For ceiling heaters, AI can optimize the radiative heat flow, particularly in larger spaces or multi-zone homes, ensuring even heat distribution while reducing energy consumption [24], [25], [26].

In this sense, this paper follows the previous study [27], in which the results of computer simulations carried out to assess the effect of thermal insulation on the thermal comfort of the monitored room of a terraced family house are presented. This paper is focused on the numerical assessment of the effect of different room heating methods on assembled room models. The study aims to create a methodology that allows determining the appropriate type of heating for a specific family house in which the monitored room is located, considering its construction and climatic conditions. Assessment of the effectiveness of floor and ceiling heating using an electric heating foil and heating with a plane radiator is carried out by numerical simulations and subsequent processing and statistical evaluation of the output data.

II. METHODS

In the simulations described below, heat transfer is assessed on a model of a room with dimensions 4.8 × 4.5 × 2.65 m, which is part of a terraced family house. The room is located under the roof, with the side and rear walls adjoining other rooms of the house and the front wall with windows and balcony doors partially adjoining the interior of the neighboring house.

The study aimed to compare the efficiency of floor heating, ceiling heating, and heating with a plane radiator placed in the observed room. Computer simulations were performed using COMSOL Multiphysics 5.3 (COMSOL, Stockholm, Sweden). The output data were processed and analyzed using MATLAB 2024b (MathWorks, Massachusetts, USA).

The geometry of the room model with the observed heating cases is shown in Fig. 1. In the cases of floor and ceiling heating, a heating foil was placed in the floor or ceiling wall, respectively.

The structure of the floor or ceiling with the heating foil is described in Table 1. Both a model with thermal insulation inserted between the heating foil and the wall and a model without thermal insulation were tested. Due to the high memory requirements of the simulations, the heating foil was not incorporated into the geometric model as a physical layer. Instead, the required parameters of the heating foil were inserted into the model as a boundary condition representing the source of supplied thermal energy. In the model with floor heating, the heating foil is assumed to be placed under the floor covering. In the model with ceiling heating, the heating foil was placed under a brick layer or thermal insulation.

Numerical simulations represent the non-stationary heat transfer between the interior of a house and the outdoors. The general equations used in the numerical solution of problems for non-stationary heat transfer by COMSOL Multiphysics software are described in the publication [28]. The specific conditions applied to the heat transfer in the monitored heated house are described in detail in our previous publication [27]. The boundary conditions of the formulated models include all heat transfer mechanisms, i.e., conduction, flow, and radiation.

Numerical methods for data resampling and polynomial smoothing were applied to process the output data because the node points of the numerical network in the assembled models were not evenly spaced. Processing of output data from computer simulations and their statistical evaluation was performed using the proposed Graphical User Interface (GUI) programmed in MATLAB (see Fig. 2).

To compare the distribution of air temperature in the room depending on the type of heating, the original three-dimensional matrix of output data was resampled to a matrix with a constant interval of distance between individual points, and then its median and mean values were calculated according to the equation (1):

$$\bar{a} = \frac{1}{N}\sum_{i=1}^{N} a_i \tag{1}$$

where $a = \{a_i\}_{i=1}^{N}$ is a finite-length vector made up of N scalar values.

A variance (V) of the **a** vector was calculated according to equation (2):

$$V = \frac{1}{N-1}\sum_{i=1}^{N} (a_i - \bar{a})^2 \tag{2}$$

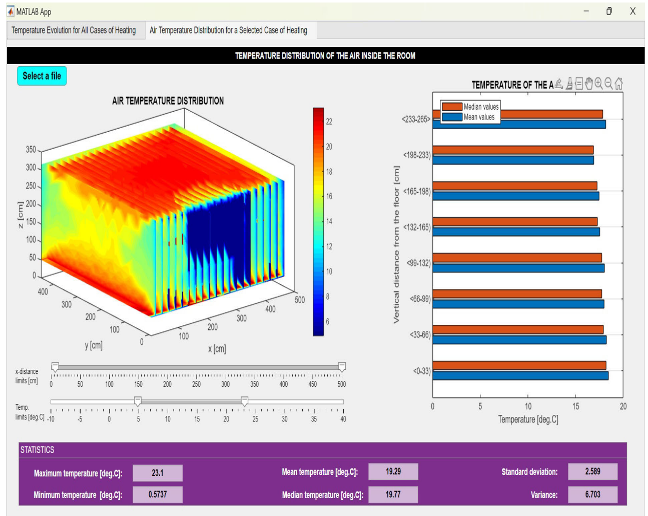

FIGURE 2. Graphical user interface for evaluation of air temperature distribution during room heating.

and a standard deviation (S) that is the square root of the variance.

The efficiency of room heating, depending on the heating method used, was also compared according to the thermal time constant, which is expressed as the time to change to 63.2% of the difference between the initial and final mean air temperatures during the heating of the room. This value was numerically calculated from an approximate exponential function (in the case of floor and ceiling heating) or a polynomial function (in the case of heating by a radiator).

III. RESULTS

A comparison of floor heating, ceiling heating, and heating with a plane radiator was carried out under winter conditions in the Central European climate zone.

Simulations were performed under the following conditions:

- initial temperature of the air inside the tested room 10°C,
- outside air temperature −10°C,
- air temperature in neighboring rooms 20°C,
- heat transfer coefficient in the interior of the house $8W/(m^2 \cdot K)$,
- heat transfer coefficient in the exterior of the building $23W/(m^2 \cdot K)$,
- surface temperature of heating foils 24°C,
- surface temperature of the radiators 40°C.

The output values of the air temperature inside the room were recorded at a time interval of 2 hours. The exported dataset is stored at the IEEE DataPort (http://ieee-dataport.org/13952) for further investigation. This repository also includes a video abstract of the paper. The average and interpolated values processed in the MATLAB are depicted in Fig. 3. In the case of floor and ceiling heating, temperature rapidly increased from the initial values, while during radiator heating, the temperature increase was low and slow. With floor heating, the air in the room warmed up during the observed time

TABLE 1. Thickness and thermophysical properties of the geometrical elements of the model.

Layer	Thickness [cm]	Thermal conductivity $[\mathrm{W/(m \cdot K)}]$	Density $[\mathrm{kg/m^3}]$	Specific heat capacity $[\mathrm{J/(kg \cdot K)}]$	Emisivity [-]
CEILING					
Roof covering (top)	0.1	237	2700	900	-
Wooden boards	20	0.05	200	850	-
Brick layer	30	0.8	1800	900	-
Thermal insulation	5	0.035	35	2050	-
Heating foil	-	-	-	-	-
FLOOR					
Floor covering (top)	1	0.18	400	2510	0.94
Heating foil	-	-	-	-	-
Thermal insulation	5	0.035	35	2050	-
Brick layer	19	0.8	1800	900	-
VERTICAL WALLS					
Front (outside) wall	45	0.8	1800	900	0.85
Back wall	30	0.8	1800	900	0.85
Left wall	30	0.8	1800	900	0.85
Right wall	15	0.8	1800	900	0.85
WINDOWS					
Glass filling	1	0.8	2600	840	0.94
Gas between the glass filling	1	1.178	1.782	720	-
Window frame	8	0.18	400	2510	0.94
DOOR					
Door in the interior of the house	5	0.18	400	2510	0.94

from an initial temperature of 10°C to a final temperature of 20.8°C. The final temperature was 20.2°C during ceiling heating. During plane radiator heating, the final temperature was only 16.2°C.

The time evolution of the air temperature concerning the height of the room is shown in Fig. 4. Floor and ceiling heating with thermal insulated walls, and heating by a plane radiator are compared. The mean temperature of the air calculated from data related to whole length (i.e., $y \in \langle 0, 450\rangle$cm) of the room is shown in Figs. 4(a)-(f). The mean temperature calculated for data related to the distance plus or minus 5 percent from the middle part of the room (i.e., $y \in \langle 202.5, 247.5\rangle$cm) is shown in Figs. 4(g)-(j). The mean temperatures related to the distance within 10 percent from windows (i.e. $y \in \langle 0, 45\rangle$cm) are depicted in Figs. 4(k)-(o).

The air temperature distribution in the room after 48 hours of heating, depending on the heating method, is shown in Fig. 5. Table 3 shows the average and median temperatures of the individual zones of the room, which represent the vertical distance from the floor to the ceiling. After floor heating without wall insulation, the average air temperature in the case of thermal insulation of the floor from the heating foil was between 20.4°C and 21.5°C. When the insulation was applied, the air temperature range was 20.6°C and 21.8°C. In both cases, the highest temperature was in the $\langle 33, 66\rangle$cm zone. With ceiling heating without wall insulation, the final average air temperature ranged between 19.5°C and 21.3°C in the case of thermal insulation of the floor from the heating foil. When the insulation was applied, the air temperature range was 19.4°C and 22.0°C. In both cases, the highest temperature values were reached in the $\langle 233, 265\rangle$cm zone. At the end of heating by a plane radiator located near the wall with windows, the average air temperature was between 17.1°C and 18.4°C. The highest mean air temperature was in the $\langle 33, 66\rangle$cm zone.

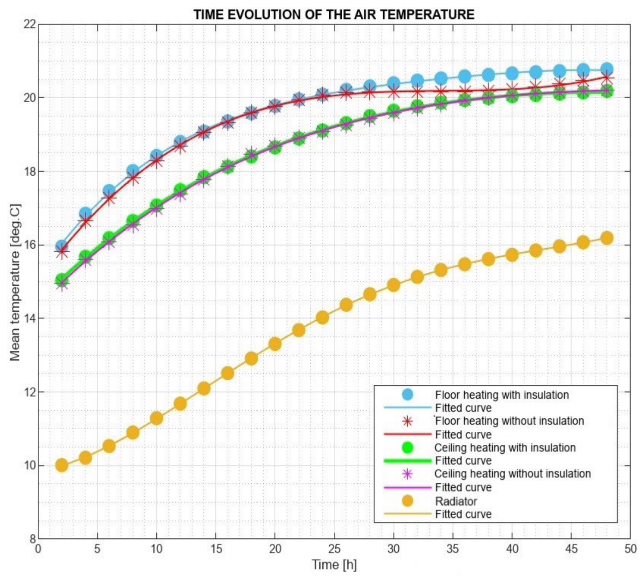

FIGURE 3. Temperature evolution of the air by floor heating, ceiling heating, and heating by a plane radiator placed in the room.

Time constants of mean air temperatures inside the studied models of heated rooms are shown in Table 2. With floor heating, both with and without thermal insulation of the floor, the value of the time constant was 5.4 hours. With ceiling heating in a room without thermal insulation, the time constant was 7.8 hours, and in the room with ceiling thermal insulation, the time constant was 8.2 hours. When heating the room with a plane radiator, the achieved value of the time constant was 23.8 hours.

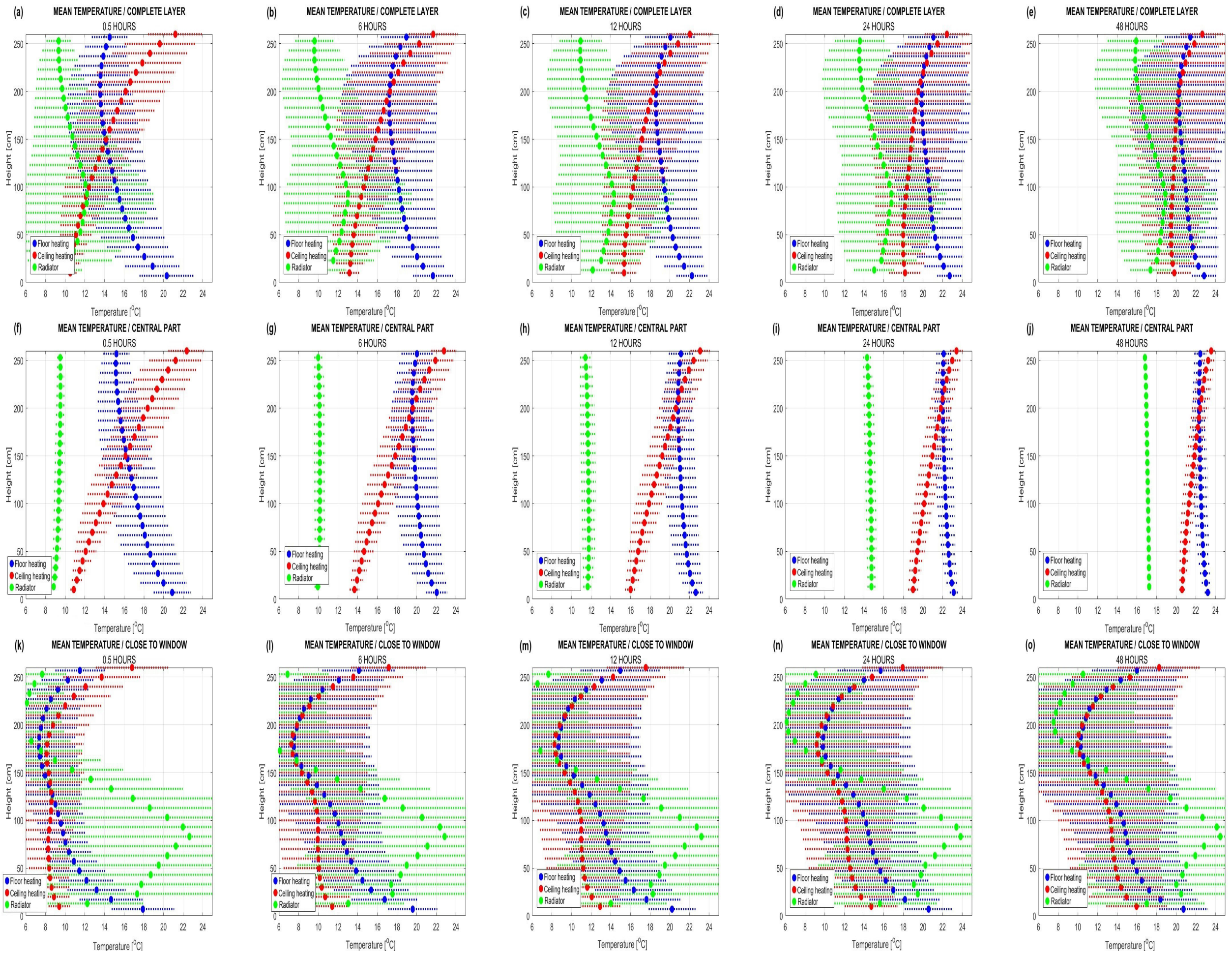

FIGURE 4. **Time evolution of the mean air temperature with respect to the height of the room during floor and ceiling heating with thermal insulated walls, and heating by a plane radiator. In cases (a) - (e), the mean temperature was calculated for data related to the entire length of the room. In cases (f) - (j), the mean temperature was calculated from data in the middle part of the room (i.e., within a distance of up to 5 percent of the length from the center of the room). In cases (k) - (o), the mean temperature was calculated from the data corresponding to the area within 10 percent of the window. Selected times of heating: 0.5, 6, 12, 24, and 48 hours. Dotted lines represent ranges of standard deviations.**

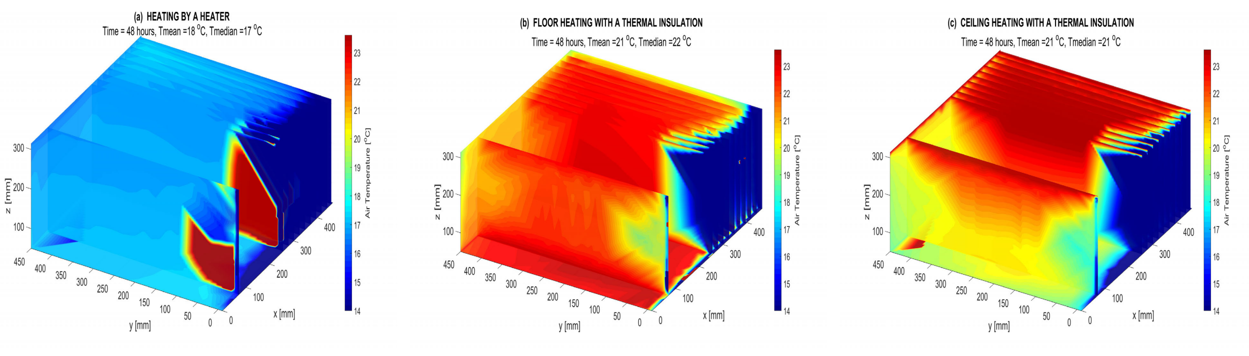

FIGURE 5. **Temperature distribution of the air inside the room: (a) heated by a plane radiator, (b) by floor heating, (c) by ceiling heating. The time of heating is 48 hours.**

IV. DISCUSSION

When it comes to computer simulations for studying heat transfer in buildings, there are several advantages and disadvantages. Simulations allow for virtual assessments of projects, identifying energy-saving changes at a reasonable cost during the building design phase. However, simulations rely on mathematical models, which may not perfectly match real-world conditions. Therefore, accurate input data and model parameters are crucial for reliable results.

It should also be noted that the calculation time depends on the specific requirements of the studied model, as well as on the hardware equipment of the computer. In this paper,

TABLE 2. Time constants of mean air temperatures inside the studied models of a heated room: IW refers to a model with a layer of thermal insulation placed in the floor or ceiling, while NIW refers to a model without thermal insulation in the floor or ceiling.

Method of heating		Time constant [h]
Floor heating	IW	5.4
	NIW	5.4
Ceiling heating	IW	7.8
	NIW	8.2
Radiator		23.8

TABLE 3. Mean and median values of the air temperature inside the room after 48 hours of heating: Ranges represent the distance from the floor to the ceiling. IW refers to a model with a layer of thermal insulation placed in the floor or ceiling, while NIW refers to a model without thermal insulation in the floor or ceiling.

Distance [cm]	Floor heating IW	Floor heating NIW	Ceiling heating IW	Ceiling heating NIW	Radiator
MEAN TEMPERATURE [°C]					
⟨0, 33)	21.8	21.5	19.4	19.5	17.8
⟨33, 66)	21.2	21.0	19.5	19.6	18.4
⟨66, 99)	20.8	20.6	19.5	19.6	17.7
⟨99, 132)	20.8	20.7	19.6	19.6	17.5
⟨132, 165)	20.8	20.6	19.8	19.9	17.5
⟨165, 198)	20.7	20.4	19.9	20.0	17.3
⟨198, 233)	20.6	20.4	20.2	20.2	17.3
⟨233, 265⟩	21.0	20.8	22.0	21.3	17.1
MEDIAN TEMPERATURE [°C]					
⟨0, 33)	22.0	21.6	19.7	19.8	17.5
⟨33, 66)	21.5	21.3	19.9	20.0	17.7
⟨66, 99)	21.3	21.1	20.0	20.1	17.6
⟨99, 132)	21.3	21.0	20.1	20.1	17.5
⟨132, 165)	21.2	20.9	20.2	20.3	17.7
⟨165, 198)	21.2	20.9	20.3	20.4	17.4
⟨198, 233)	21.1	20.8	20.6	20.4	17.3
⟨233, 265⟩	21.4	20.9	22.2	21.0	17.1

all models were formulated under simplifying assumptions due to the computational complexity being limited by the demands on computing power and operational memory of the computing device used. The simulations were performed on a computer with 84 GB of RAM. The average duration of one simulation ranged from approximately 24 to 72 hours, depending on the geometric layout of the model, physical properties of individual elements, boundary conditions, and other specific settings such as the properties of the numerical computational network and the time step of the calculation.

On the other hand, combining artificial intelligence with simulations of heat transfer in buildings can significantly enhance the accuracy and efficiency of numerical analysis methods. Data obtained from numerical simulations can be used to create algorithms that optimize input parameters, boundary conditions, and heat source configurations of heat transfer models. Computational intelligence can be used for digital signal processing in many engineering applications [29]. AI can be integrated with many sensors in a smart heating system to monitor real-time data and dynamically adjust heating parameters. Additionally, AI can predict temperature distributions and heat fluxes based on historical data and simulation results. By analyzing large datasets from simulations and experiments, AI can uncover patterns and relationships that might not be evident through traditional methods [26].

The possibility of using COMSOL software to study the thermal behavior of buildings was explored in the work [27], where the same family house was tested, and the results of computer simulations were verified with data recorded by a thermal camera.

The distribution and time evolution of the air temperature in the room are influenced by many factors, such as furniture placement and the presence of people, which were not considered in the presented simulations. However, the results show that the speed and efficiency of floor and ceiling heating are higher than heating with a panel heating element. While the maximum increase in the air temperature in the room is recorded during 24 hours of heating when using the floor and ceiling foil, the increase in the air temperature in the room is gradual when heating with a panel radiator. The highest rate of room heating is recorded in the case of floor heating, for which the time constant is determined to be more than four times higher than in the case of heating with a plane radiator. In the case of ceiling heating, the time constant is approximately three times lower than in the case of heating with a plane radiator.

Computer simulations also monitored the effect of incorporating thermal insulation between the heating foil and the wall of the floor or the ceiling of the room. However, under the considered conditions, the thermal insulation layer has almost no effect on the air temperature. A possible reason is that a small thickness of the material is tested due to its thermal insulation properties.

Heat transfer using all the compared methods involves conduction and radiation. From the point of view of air temperature distribution, the results show significant differences, which are caused by differences in design, location of the heating devices, and the prevailing heat transfer mechanisms. With floor and ceiling heating, the air temperature in all parts of the room is more uniform compared to heating with a plane radiator. The plane radiator warms the air directly around it. As this air heats up, it becomes less dense and rises, allowing cooler air to move in and be heated in turn. This creates a circulation of warm air throughout the room. During ceiling heating, a heating foil emits infrared radiation, which directly warms the objects and surfaces in the room, including the floor and furniture. This combination ensures a comfortable and evenly distributed warmth throughout the room. During heating by a floor heating foil, the heat transfers to the floor material through direct contact. This heat then spreads across the floor surface, warming it up. The heated floor surface emits infrared radiation, which warms up the objects and people in the room.

Computer simulations and subsequent processing and evaluation of the output data of the monitored heating methods make it possible to obtain more detailed information on the distribution of the temperature of the walls and the air in the room with respect to the height (i.e., distance from the floor) than could be determined using experimental methods.

V. CONCLUSION

Computer simulations of heating a room in a family house with a floor heating foil, a ceiling heating foil, and a plane radiator provide a detailed view of the efficiency of the monitored heating methods and their effect on thermal comfort and energy efficiency.

The results show that floor and ceiling heating systems are more effective and efficient for maintaining comfortable indoor temperatures in winter conditions compared to heating with a plane radiator. Floor heating, in particular, offers the most uniform temperature distribution and highest final temperatures.

The paper presents the proposed GUI for a quick and clear assessment of the results obtained by simulations. The GUI performs basic statistical evaluation and 3D visualization of the air temperature distribution within the room.

It is obvious that when studying the properties of buildings, it is necessary to observe from many points of view, including heat transfer, moisture transfer, and other influences essential to comply with the required comfort and hygiene criteria. This work is focused on a detailed assessment of the effect of heating in terms of heating speed and air temperature distribution in the room. It is assumed that future studies will focus on assessing the influence of individual heating methods in terms of temperature and humidity distribution in the building construction materials. This is also related to the assessment of the application of suitable thermal insulation material in the walls of the room.

Connecting the simulation of heat transfer with artificial intelligence tools can significantly enhance the accuracy and efficiency of numerical analysis methods. Further investigation should be devoted to heating optimization using selected artificial intelligence tools.

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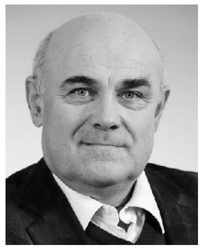
HANA CHARVÁTOVÁ received the Ph.D. degree in chemistry and materials technology from the Faculty of Technology, Tomas Bata University in Zlín (TBU), Zlín, for the Technology of Macromolecular Substances, in 2007. Currently, she is associated with the Centre for Security, Information and Advanced Technologies (CEBIA–Tech), Faculty of Applied Informatics, TBU. Her research interests include modeling manufacturing processes of natural and synthetic polymers, analysis of thermal processes in building technology, studies of sensor system and wireless communication, signal processing for motion monitoring, and modeling of engineering and information systems. She is oriented towards computational and visualization methods in thermographic, spatial modeling, and engineering. She serves as a Reviewer for Springer, Elsevier, Wiley, *Taylor and Francis*, and MDPI journals.

ALEŠ PROCHÁZKA (Life Senior Member, IEEE) received the Ph.D. degree, in 1983. He was appointed as a Professor of technical cybernetics with Czech Technical University, in 2000. He is currently the Head of the Digital Signal and Image Processing Research Group, Department of Computing and Control Engineering, University of Chemistry and Technology at Prague (UCT), and Czech Institute of Informatics, Robotics, and Cybernetics, CTU, Prague. His research interests include mathematical methods of multidimensional data analysis, segmentation, feature extraction, classification, and modeling in biomedicine and engineering. He is a member of IET and EURASIP. He has served as an Associate Editor for *Signal, Image and Video Processing* (Springer) journal. He is a reviewer for different IEEE, Springer, and Elsevier journals.

MARTIN ZÁLEŠÁK received the Ph.D. degree in energy machinery and equipment from CTU Prague, in 1981. Currently, he is a Senior Lecturer with the Department of Automation and Control Engineering. He is associated with the Centre for Security, Information and Advanced Technologies (CEBIA–Tech), Faculty of Applied Informatics, Tomas Bata University in Zlín (TBU), Zlín. His research interests include problems of building physics and systems of environmental technology, construction of laboratories of building physics, environmental technology, solutions for energy-saving measures in the industrial environment, and issues of integrated building systems. He is a member of Czech Standardization Institute and the Czech Chamber of Authorized Engineers and Technicians. He serves as a forensic expert in building environment technology and as an energy specialist.



VLADIMÍR MAŘÍK (Life Fellow, IEEE) received the M.Sc. and Ph.D. degrees in control engineering from Czech Technical University in Prague. He is currently the Scientific Director of the Czech Institute of Informatics, Robotics, and Cybernetics, Czech Technical University in Prague, and the Head of the Intelligent Systems Research Group with a focus on artificial intelligence, machine learning, large-scale parallel computations, distributed multiagent systems, and theories of complex problems. His research interests include devoted to soft-computing, dynamic optimizations, environmental informatics, and computer-integrated manufacturing. Applications include the development of smart cities, proposals of intelligent transportation systems, and implementation of advanced systems for education.