Civil Engineering and Architecture 11(2): 930-938, 2023 http://www.hrpub.org
DOI: 10.13189/cea.2023.110229

Energy Saving through Automation of the Lightweight Floor Heating System

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Received October 17, 2022; Revised December 12, 2022; Accepted December 23, 2022

Cite This Paper in the Following Citation Styles

(a): *[1] Oleksandr Nedbailo, Boris Basok, Ihor Bozhko, Maryna Novitska , "Energy Saving through Automation of the Lightweight Floor Heating System," Civil Engineering and Architecture, Vol. 11, No. 2, pp. 930 - 938, 2023. DOI: 10.13189/cea.2023.110229.*

(b): *Oleksandr Nedbailo, Boris Basok, Ihor Bozhko, Maryna Novitska (2023). Energy Saving through Automation of the Lightweight Floor Heating System. Civil Engineering and Architecture, 11(2), 930 - 938. DOI: 10.13189/cea.2023.110229.*

Abstract The overview of the literature sources showed that over the last decade, the attention to the study of heat transfer processes with the automation and periodic use of underfloor heating systems has increased significantly. The aim of this study was to investigate the heat flux density from the surface of the lightweight floor heating system dependence on different parameters. These parameters are material of the finishing coating, average temperature difference between indoor air and heat carrier, heat carrier temperature and its flow rate, thickness of the thermal insulation layout under the lightweight floor heating system. The article shows results of both experimental and computational modelling studies of the lightweight floor heating system which was operated in different regimes and with different (ceramic tile and laminate) finishing coatings. A new experimental stand has been created in the thermophysical laboratory of the Institute of Engineering Thermophysics of the National Academy of Sciences of Ukraine for the purposes of experimental studies. For the purposes of comparison of different operational regimes as well as the determination of the energy saving through automation of the operation regimes of the lightweight floor heating system, the CFD modelling was conducted. The results showed that such systems have significant potential for automation and heat supply purposes of different premises since they have low thermal inertia due to the absence of the concrete screed monolith. On the other hand, the research showed that use of quantitative regulation of the lightweight floor heating system, by reducing the flow of the heat carrier is more effective in this case than qualitative with change of heat carrier temperature.

Keywords Heating, Energy Efficiency, CFD Modelling, Automation, Energy Saving

1. Introduction

The underfloor heating systems proved themselves as an effective technology in order to reduce energy consumption and to provide thermal comfort of users in different types of buildings including energy-efficient ones. The use of such system is widespread in Ukraine and around the world. Currently, there are two types of such systems, the traditional underfloor heating system [1, 2] and the lightweight floor heating system [3, 4]. In traditional underfloor heating systems, the pipe is situated in a layer of cement-sand screed, which lies above the insulation and is covered with a finishing coating. And in the lightweight floor heating systems, the cement-sand screed is not used. The pipes with heat carrier in it are connected to the aluminum heat-spreading plate. The plate, in its turn, connected to the insulation layer and all this system is covered with a finishing coating.

2. Literature Review

The overview of the literature sources showed that there are a lot of factors which influence on the efficiency of the lightweight heating system – the temperature of the heat carrier, the diameter of the pipe, the thickness of the insulation layer, the pipe layout, the thickness and thermophysical properties of the finishing coating material, etc. The studies of the influence of these parameters on the efficiency of underfloor heating systems are widely presented in the literature. The total amount of works can be divided into sections: CFD (computational fluid dynamics) simulations [1, 2, 5], experimental studies [6] and hybrid studies (works that combines both simulations and experimental research) [3, 4].

Over the last decade, a lot of scientific works have studied the automation of the heat transfer processes for these systems and this number constantly increases [5, 6].

Article [5] presents results of fundamental theoretical studies. The aim of these studies is to investigate the impact of automation of a common underfloor heating system on heat transfer in a premise that is being under the influence of changing environmental conditions. The authors consider heat exchange in an enclosed room volume, with panoramic windows and underfloor heating system. The problem has been solved using a two-dimensional unsteady formulation. Above the location of the underfloor heating system as the boundary condition, the heat flux was set, and the magnitude of which depended on temperature of the environment. The temperature of the environment was determined by the sine function. Among others, the authors considered the influence of the size of the underfloor heating system on the heat transfer in the room. The authors concluded that radiation has a much bigger influence than convection. The size of the underfloor heating system significantly affects the picture of heat transfer to the room. Another conclusion is that the emissivity of the room surface has the least influence compared to other parameters.

In article [6], the scheme of underfloor heating control system with the use of controllers and algorithms of machine learning is described. The authors claim that the application of this approach has three advantages. First of all, such a system has the potential to solve the overheating and underheating problems that are typical for central heating systems. Secondly, temperature control could be introduced in a separate premise of the building (or its part). Thirdly, it is possible to operate systems remotely – this increases comfort of consumers. However, the authors also noted some disadvantages of the proposed system, namely the high cost of implementation of such control systems, the presence of a large number of automatic valves, which increase the risk of failure, and the fact that the system delivers data and software, which, according to the authors, complicates system maintenance and management.

One of the objectives of this research is to conduct a comprehensive study and development of controlling methods for the automated system of lightweight floor heating system.

3. Methodology

Experimental studies were conducted on a stand in the thermophysical laboratory of the Institute of Engineering Thermophysics [7]. The piece of the lightweight floor heating system with an area of 6.36 m^2 and dimensions of 1.2 m × 5.3 m was installed in the middle of the laboratory premise with total area of 18 m^2. The premise dimensions were as follows: width 3 m, length 6 m and height 3 m. The lightweight floor heating system installation scheme is shown in Figure 1.

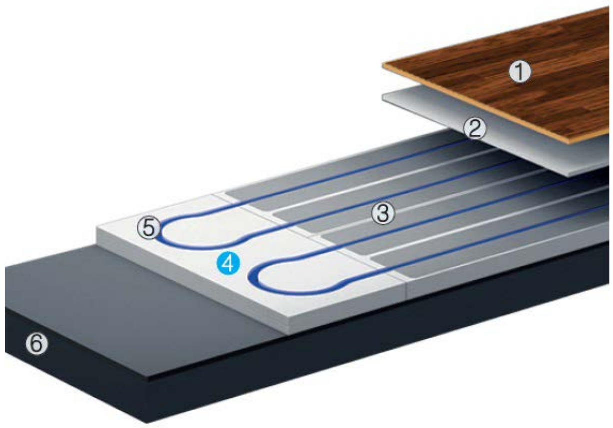

Figure 1. Scheme of lightweight floor heating system: 1 - system's finishing coating (laminate or ceramic tile); 2 – substrate layer (either cellulose or gypsum fiber); 3 - heat-spreading plate made of aluminum; 4 - thermal insulation - polystyrene plate; 5 - heating circuit pipe; 6 - base floor of the premise

The underfloor heating circuit is made of standard metal-polymer pipe PeX (DN 16x2 mm). The aluminum heat-spreading plate and insulation polystyrene plates with grooves (channels) were used, and their thickness was 0.2 mm and 40 mm, respectively.

With the help of such a technical solution, the room premise had constant temperature in accordance with sanitary and hygienic norms (indoor air temperature is 20 ± 2ºC) in quasi stationary conditions. Depending on the change of the in- and outdoor air temperature, the value of electric power (heat load) on instantaneous electric water heaters was discrete set. The electric water heaters were used to compensate for heat loss of the room's premise. The underfloor heating system worked at a constant flow rate condition.

During the experimental study regimes, heat load has been discretely set and had values of: 200, 300, 400, 500 and 600 W respectively. The stabilized source SSK-1-3-220 of electric current 220 V, 50 Hz together with the electric water heater VPO-5.5/220 were used in order to regulate the power of lightweight floor heating system. Also, we used portable measuring kit K-50, which recorded the current, voltage and power and a laboratory autotransformer RNO-250-5 as auxiliary equipment. Within each regime, the experiment continued until the constant distribution of the temperature field in the air above the finishing coating and in the layers of the underfloor heating system of the premise (no change in temperature and heat flux in the characteristic measurement locations) has been reached. Depending on the heat load, the time before reaching the quasi-stationary mode of operation of the experimental system with laminate coating was from 8 up to 12 hours.

Significant daily fluctuations in ambient air temperature during the experiments caused a change in the total heat loss of the premise. Increasing heat losses of the premise caused longer achievement of the quasi-stationary heat transfer mode since the heat flux density from the surface of the sample has been limited due to the temperature limitations of the heat carrier at the lightweight floor heating system inlet. This was because the fact that lightweight heating system has a heat transfer surface area less than the total area of the premise due to the need to properly assemble and operate.

Experimental studies consisted of real-time measurement of heat flux density, temperature in specific places of the lightweight floor heating system and air temperature in premise with the help of the thermoelectric sensors. During the experiments, records of lightweight floor heating system parameters with 10 minutes intervals were made. All data were recorded by a system of secondary control. Those were the following values:

- air temperature in premise in 16 points throughout height of the room (for further determination of the average indoor air temperature *t*);
- outdoor air temperature;
- temperature at various specific places of the lightweight floor heating system (on surface of the finishing covering above the supply and return pipes).Also, in different places that correspond to the heating circuit in horizontal projection and vertical as well –between layers of the lightweight floor heating system starting from -430.0 up to 0.0 mm and also under the thermal insulation;
- heat carrier's temperature at the inlet and outlet of the lightweight floor heating system;
- the heat flux density under the lightweight heating system, between different layers and on the system's finishing coating in the specific places of the heating circuit (see rectangular marks in Figure 2).

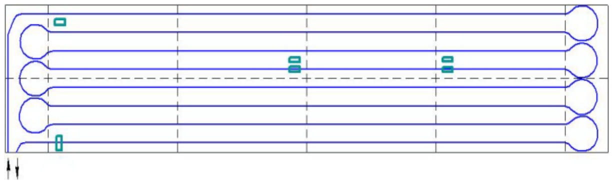

Figure 2. Sensors (green rectangles) placement scheme in the lightweight floor heating system

For determination of the lightweight floor heating system's heat load (that was set by the electric water heaters) the Apator LQM-III-K heat meter was used, which has been installed at the system's inlet.

4. Result and Discussion

During all experiments, days with minimal daily fluctuations in environment air temperature and wind speed were selected. This provided the maximum proximity to the constant heat loss of the room over time. According to the state regulations, in the zones of the most significant cooling of the premise (near the external enclosing structures), the lightweight floor heating system's surface temperature should not exceed 35 ºC. This also has been considered during experiments (respectively, the heat load was regulated). The total relative error of measurements of basic physical quantities in the automatic mode didn't exceed 5%. During the series of experiments that were performed, the heat carrier flow rate in the floor heating circuit inlet was G = 0.102 and 0.058 m^3/h. There were used different expanded polystyrene board thickness of 40, 50 and 80 mm. Both, laminate and tile were used as the finishing coating. The 8 mm thick laminate was laid according to the technology on a 4 mm thick cellulose substrate. The 8 mm thick ceramic tile has been glued with a special mixture directly to the aluminum heat-spreading plate.

The experiments results are shown in Figures 3-5.

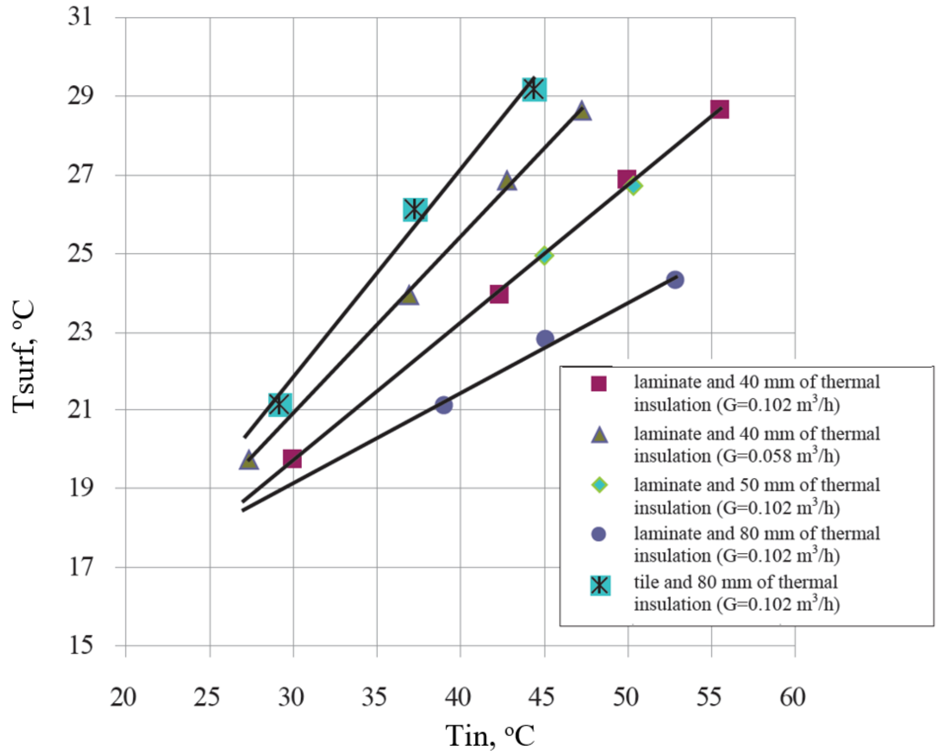

Figure 3. The average floor surface temperature dependence on the heat carrier's temperature at the lightweight floor heating system inlet

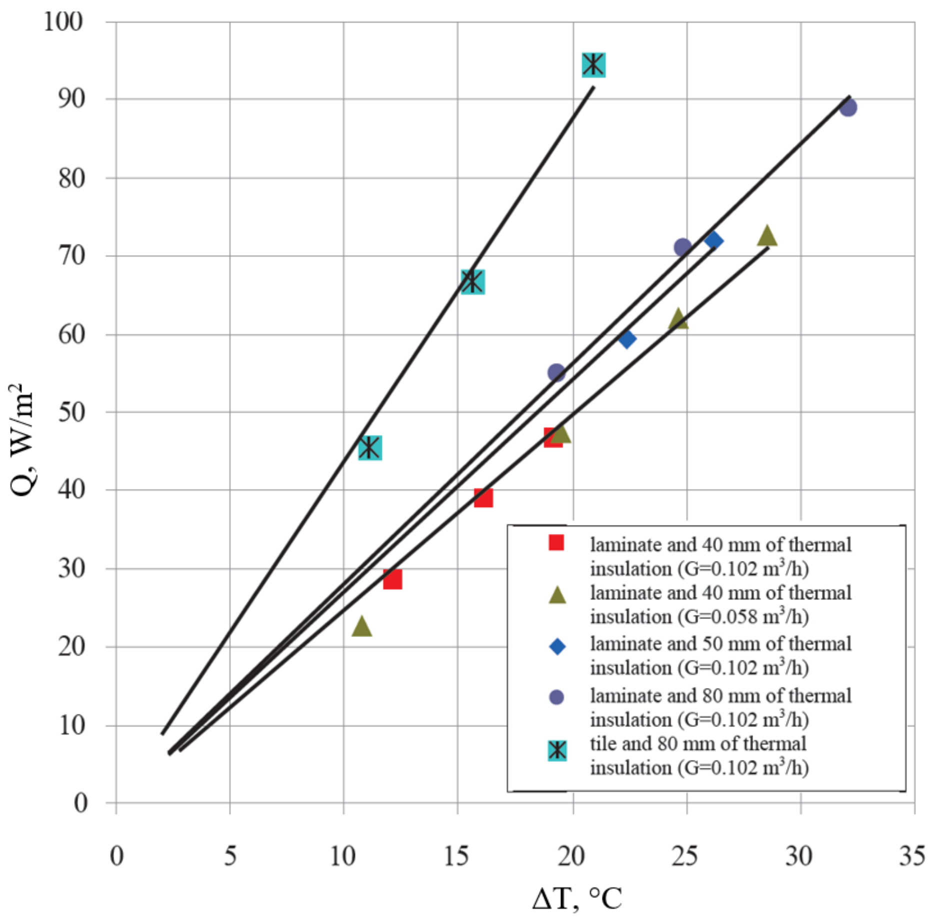

Figure 4. Dependence of heat flux density on the average difference in heat carrier's and indoor air temperature

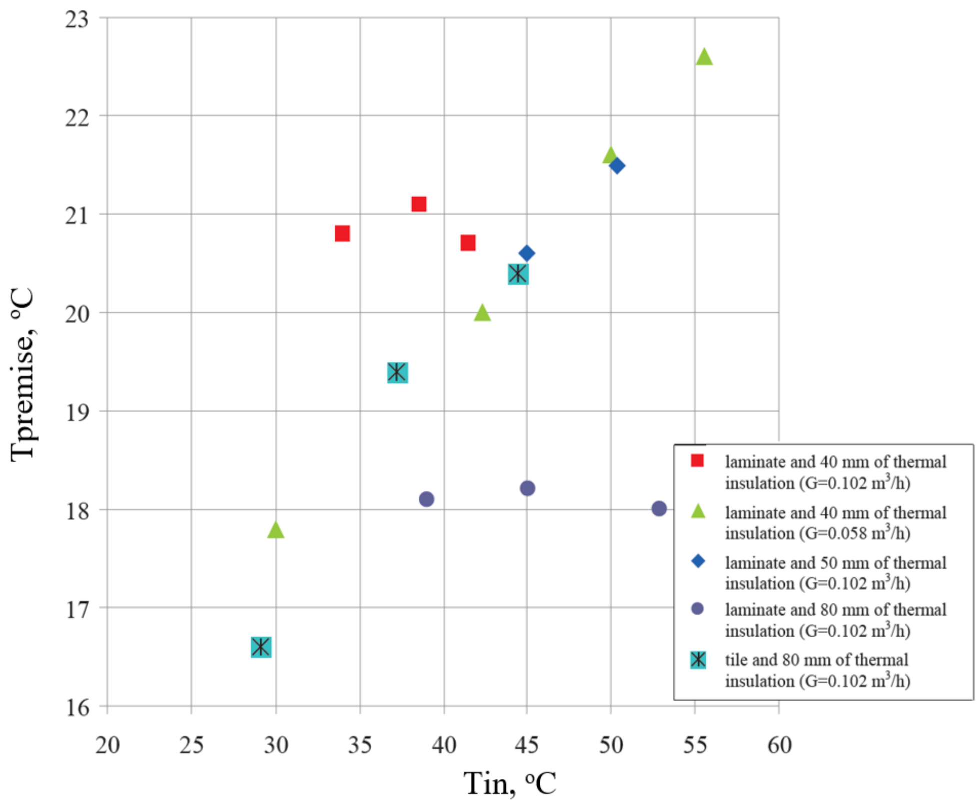

Figure 5. Dependence of the air temperature in premise on the heat carrier temperature at the underfloor heating circuit inlet

The obtained experimental data were used to validate the CFD model.

4.1. CFD Modelling Studies

Simulations using CFD model of the system fragment shown in Figure 6 were performed. Thermophysical properties of the used materials are presented in Table 1.

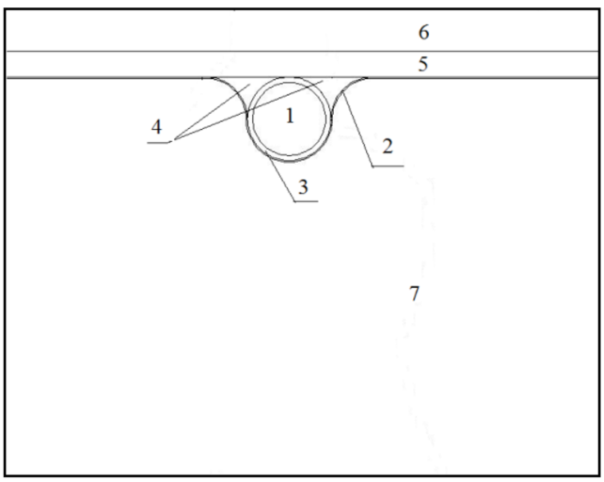

Figure 6. The cross-section of the calculation domain

Figure 6 shows calculation domain, which was used for performance of simulations, here: 1 - heat carrier inlet to the heating circuit; 2 - heat-spreading plate (aluminum 0.2 mm); 3 - polymer PeX pipe Ø16 mm, wall thickness 2 mm; 4 - air layers; 5 - tile adhesive (or laminate substrate); 6 - ceramic tile of 8 mm (or laminate of 8 mm); 7 - insulation of polystyrene foam.

The simulation was performed based on momentum and energy system of equation. The system of differential equations consisted of equations of continuity, motion and energy for the heat carrier (water), as well as the equations of thermal conductivity for the *i*-th system's layer characterized the process of heat transfer and hydrodynamics in the lightweight floor heating system. The following assumptions were used in the model:

- all materials are homogeneous, and their thermophysical properties retain constant values, as shown in Table 1.
- it is considered that the absence of boundary sections where the pipe makes a U-turn will not significantly affect the calculation result.

Boundary conditions of the third kind with a heat transfer coefficient of 8 W/(m^2·K) and ambient temperature *Tout* were set on the floor surface. The emissivity of the material ε was 0.9.

Symmetry conditions were set for all lateral surfaces (heat carrier inlet and outlet). On the lower surface of the fragment, the boundary conditions of constant temperature of 10 °C were set. Heat carrier's temperature *Tin*, °C and flow rate *Qin*, m^3/h at the inlet were set as well.

Table 1. Thermophysical properties of materials of lightweight underfloor heating system

Material name	**Thickness, mm**	**Density, kg/m^3**	**Thermal conductivity, W/(m·K)**	**Specific heat capacity *Cp*, kJ/(kg·K)**
Thermal insulation - polystyrene plate	80	40	0,031	1,34
Aluminum	0,2	2700	200	920
Laminate substrate	3	250	0,05	0,9
Laminate	8	940	0,2	1,5
Tile adhesive	5	1600	0,47	0,84
Ceramic tile	8	2000	0,89	0,88
Polymer PeX pipe	2	1500	0,43	2,3

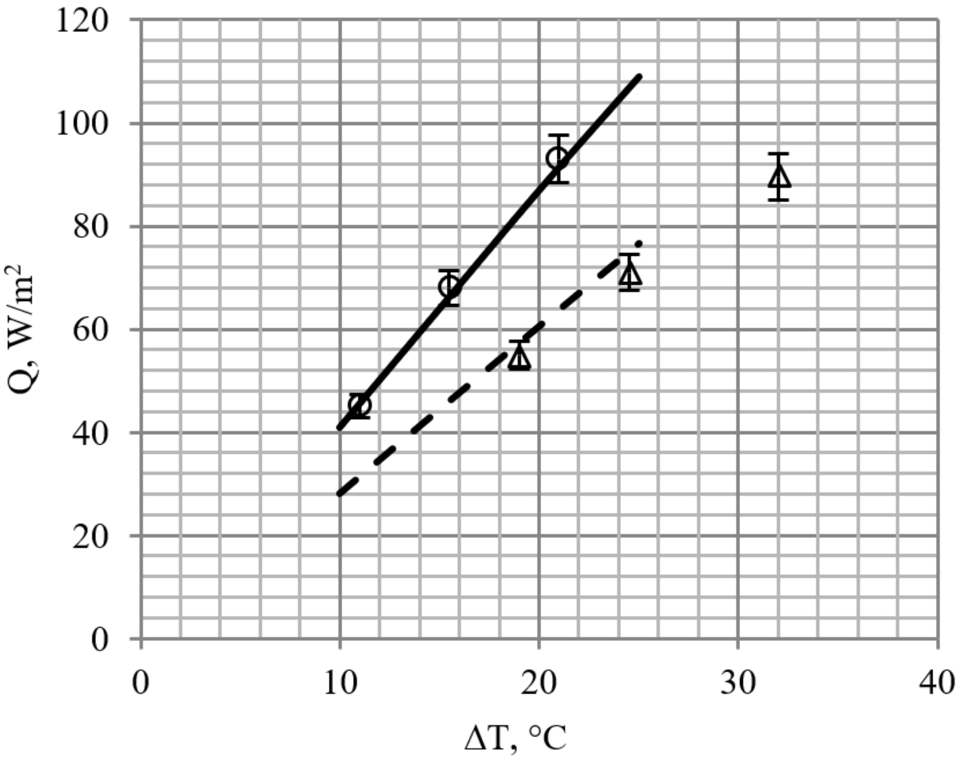

Figure 7. The heat flux density from the lightweight floor heating system's surface dependence on the average temperature difference between heat carrier and premise air

A. Model Validation

The calculation was performed for the steady operation mode of the underfloor heating system. Numerical simulation was carried out with the condition of the heat carrier's laminar flow in the pipe. The experimental data and the data of numerical simulation were compared. The results of the comparison are shown in Figure 7.

Figure 7 shows results of calculations with use of the laminate (- - - -) and ceramic tile (———) as finishing coating. Also, there are experimental data for finishing coating by laminate (Δ) and experimental data for finishing coating by ceramic tile (○).

The simulation results show a slightly higher value of the average surface heat flux from the surface of the finishing coating than experimental data. This can be explained either by the difference of the thermophysical properties of the materials, or the limitations of the CFD model. Despite this fact, the numerical model of the lightweight floor heating system's heat transfer processes is considered to be correct.

B. Parametrical Analysis

In this study, the influence of such parameters as the thickness of thermal insulation layer, heat carrier flow and its temperature was analyzed. There are two types of finishing coating: ceramic tile and laminate. The results of simulation are presented in Figures 8-10.

Analyzing Figure 8, we can conclude that increasing the temperature of the heat carrier on inlet for other equal conditions increases the heat flux per unit area of the underfloor heating system by about 13% (for every 10 °C) when using ceramic tiles and 11% (for every 10 °C) when using laminate as a finishing coating.

Calculation results that represented on Figure 8 show that increasing the temperature of the heat carrier on inlet for other equal conditions increases the heat flux per unit area of the underfloor heating system by about 13% (for every 10 °C) when using ceramic tiles (———) and 11% (for every 10 °C) when using laminate (- - - -) as a finishing coating.

Calculation results that represented on Figure 9 show that doubling the heat carrier flow rate for other equal conditions increases the heat flow per unit of the lightweight floor heating system's surface by 13% when using ceramic tiles (———) and 10% when using laminate (- - - -) as finishing covering accordingly.

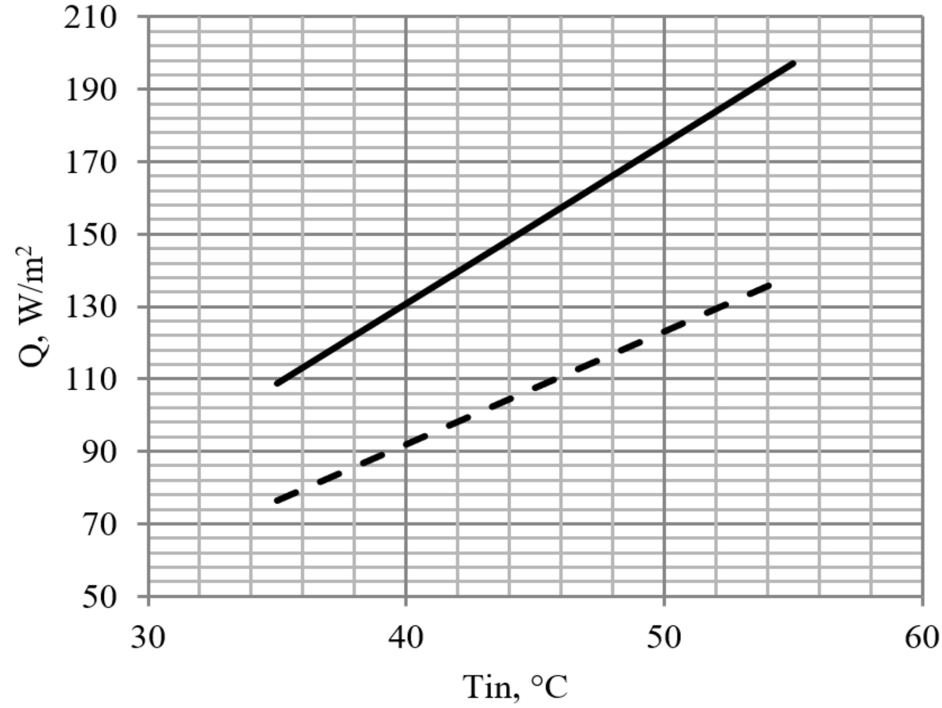

Figure 8. Heat flux density per unit of the lightweight floor heating system surface dependence on the heat carrier temperature

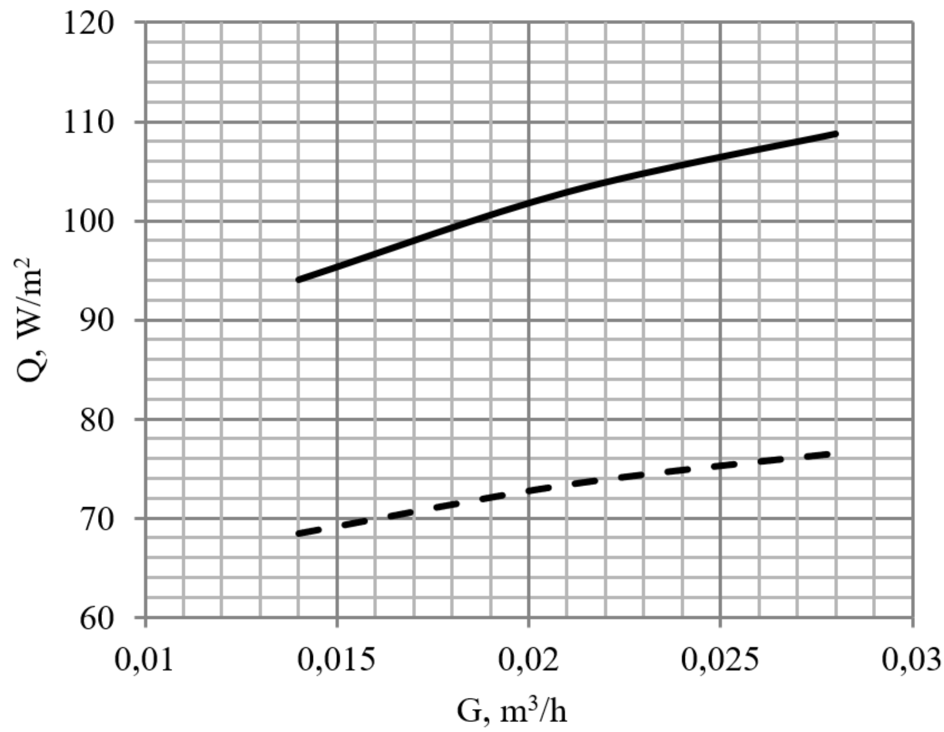

Figure 9. Heat flux density per unit of the lightweight floor heating system surface dependence on heat carrier flow rate

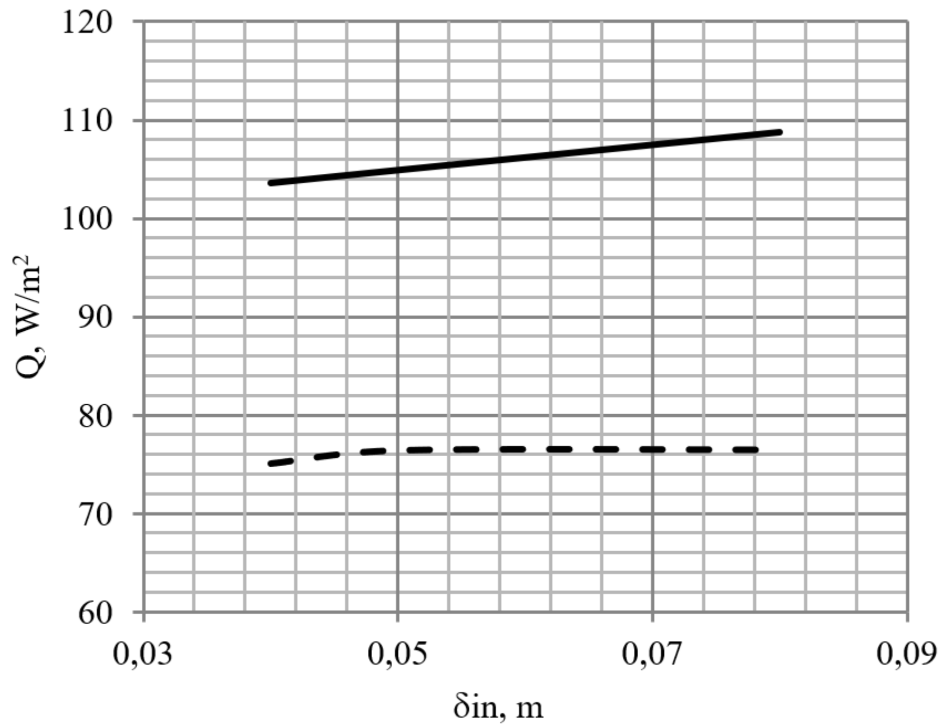

Figure 10. Heat flux density per unit of the lightweight floor heating system surface dependence on the thickness of the polystyrene plate

With increasing thickness of thermal insulation under the system (from 40 mm to 80 mm), the heat flow from the lightweight floor heating system surface increases by 4% for finishing coating made of ceramic tile (———). And about 1.6% for finishing coating made of laminate (- - - -) under the same temperature at the lower boundary of the simulation zone.

4.2. Control System

Low-temperature heating systems can work without reducing the level of consumer comfort. Every premise of the building can be equipped with a controlled lightweight underfloor heating system, which will help to timely regulate the temperature in it and reduce total expenditures on heating.

From the perspective of energy saving and comfort, it is reasonable to regulate and control the temperature in the premises during the heating period. In the case of the lightweight floor heating system usage, the control system provides additional opportunities for energy savings due to a smaller (compared to traditional) inertia of the system.

The system control unit seems to have excellent capabilities for adjusting the average temperature and flow rate of the lightweight floor heating system's heat carrier inlet, as well as adjusting the start/stop time of the heating system.

5. Recommendations

The energy saving methodology using lightweight floor heating system consists of the following steps:

- Most of energy saving potential should be performed at night with the system's turn off during the sleep period of residents of the building. During this period, it is envisaged to reduce the temperature in the specified premises. Afterwards those premises would be heated up because of created mode that will ensure rapid heating of the room with high heat carrier temperature and flow rate.
- By introduction of the schedule of residents' presence according to their lifestyle, we provide the possibility of premature switching on only of the premises used by the residents. Therefore, the lightweight floor heating system will allow to turn the heating system on or off in advance at an unscheduled time.
- Creation of a user-friendly management interface is recommended in order to increase system's energy efficiency. In real life, users may not be able to control the system due to the difficulty of programming schedule changes in the controller.

6. Conclusions

Experimental studies that have been carried show that the lightweight floor heating system has greater thermal maneuverability compared to the classical "screed using" systems, as well as low heat storage capacity. Low thermal inertia is achieved by the absence of the concrete screed.

Because of use of the aluminum heat-spreading plate, the heat flux is equal for all the planes of the finishing coating surface. This has a strongly positive effect on the heat flux distribution and reduces thermal stresses in the finishing coating.

The use of quantitative regulation of the lightweight floor heating system, by changing the flow rate of the heat carrier, is more effective than qualitative with change of its temperature.

Increasing the heat flux density from the finishing coating surface demands higher heat carrier temperature and flow. As well as the use of the automation system can significantly increase the energy saving potential of the lightweight floor heating system.

From the other hand, lightweight floor heating has also shortcomings – absence of screed increases system's vulnerability to mechanic damage, especially while using a finishing coating made of laminate, as well as great thermal maneuverability leads to possible system's freezing in case of long-term power cuts.

But despite the shortcomings, we see great potential for further research of the lightweight floor heating system by studying the efficiency of usage of different insulation materials as well as finishing coatings.

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