Ryszard NIEDBAŁA, Marcin WESOŁOWSKI, Hala Al.-DULAIMI, Adam CZAPLICKI

Politechnika Warszawska, Instytut Elektroenergetyki

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Minimization of energy consumption in underfloor heating systems

Streszczenie. *Niniejszy artykuł związany jest z problematyką energochłonności w aplikacjach związanych z elektrycznym ogrzewaniem podłogowym Rozważono wpływ istotnie odmiennych stałych czasowych elementów konstrukcyjnych ogrzewanego obiektu, na pracę podłogowego układu grzejnego. Podano różnice w sposobie ogrzewania przy użyciu regulatorów temperatury oraz regulatorów energetycznych, szczególnie w odniesieniu do zmiennych warunków klimatycznych i możliwości korzystania z tańszej taryfy energetycznej. Wykorzystanie proponowanych rozwiązań umożliwi racjonalizację konstrukcji układów grzejnych oraz algorytmów sterowania, gwarantujących zmniejszenie kosztów eksploatacyjnych. (**Minimalizacja zużycia energii w systemach ogrzewania podłogowego**)*

***Abstract**. The article deals with energy consumption and efficiency problems in electrical underfloor heating applications. Influence of structural elements of electrically heated building, defined by different time constants, on operating characteristics of heating system were discussed. Significant differences between temperature and energetic controllers were shown, especially in respect of variable climatic conditions and possibility to use of G12 tariff. Utility of calculation results, presented in the article can be a significant factor that enable to rational construction of multi-circuit underfloor heating systems and control algorithms.*

Słowa kluczowe: ogrzewanie pomieszczeń, akumulacyjne ogrzewanie podłogowe, sterowanie mocą grzejną.
Keywords: underfloor heating systems, control of heating power.

Introduction

Many different electrical heating systems are nowadays used in warming applications, as domestic, as industrial. In this article the underfloor heaters were discussed and examined. Such heating systems seem to be a very interesting in practical and economical point of view. In many cases, they are characterized by high accumulative energy values. This advantage enables to use a cheaper electricity pricing. In combination with various environmental conditions, underfloor heating systems create new possibilities of control systems and applications to improve their efficiencies.

Electrical underfloor heating systems are defined as a power source devices. Such a solution is, with respect to many constant – temperature water systems, characterized by many advantages. Heat fluxes can be precisely located and controlled by changing distances between electrical cables. Additionally the multi-circuit underfloor heaters enable widely variable division of heating power. This feature provides the possibility to use different heating sections that are placed in different depth. According to this feature different temperature distribution and different dynamic heating characteristics can be achieved. Furthermore advantages of electrical underfloor heating systems lays from no place required for boilers and fuel storage [1].

Electrical warming systems are cheaper during investment and are characterized by faster responses in comparison to the water warming systems. They not require any maintenance except of inspection and adjustment of automation components. From the technical point of view, the electrical heaters can be used as main warming system in domestic applications. Only disadvantage in Poland results from energetic certificates. According to applicable laws, ratio of received electrical energy in reference to GGS should be calculated with factor of 3. Similar ratio for wood or hard coal furnaces is of 1,1 [2].

Average energy consumption

In the article a typical storey building was analyzed. All walls were made from aerated concrete and insulated with styrofoam. The attic was insulated with mineral wool. Total surface of windows and doors was at 15% of all walls surface. Thermal resistances were calculated for every part of the building and were used to determine heat loses related to minimal, average and maximal temperatures that were averaged for a month. All results were calculated for the time when heating power was on. The power value results from appropriate climatic zone (-20ºC). In the figure 1 the time averaged exploitation times for maximal, average and minimal temperatures have been shown. Black dots show the case when building was not appropriate heated in the case of minimal temperatures.

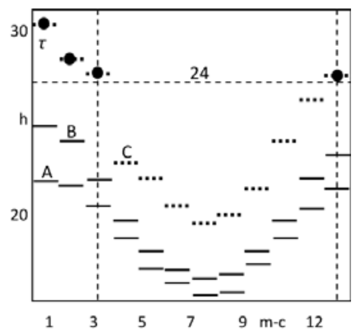

Fig. 1. Operating times of warming systems for monthly averaged temperatures: maximal (A), average (B) and minimal (C)

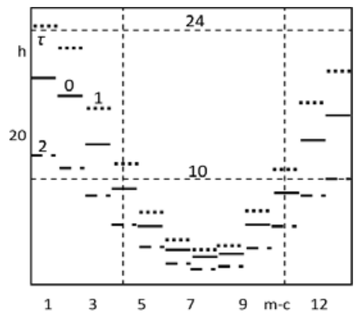

Fig. 2. Operating times of underfloor heating systems with single- and two heating circuits for monthly averaged temperatures

In the figure 2 one can observe average time values, when one circuit underfloor system was heated (0 curve). This case was presented for monthly average temperatures and a single-zone exploitation. Curves (2) and (3) shows similar cases, but two-circuits systems were analyzed.

Power division was at 1/3 (curve 1) and 2/3 (curve 2) respectively.

Basing on results shown in figure 2, there is a need to divide heating circuits of underfloor systems into few sections when one use a G12 tariff. Full heating power is switched on only sporadically. In exploitation and energetic point of view, underfloor systems of lower power values are charged by longer time intervals and, for this reason, are characterized by better factors.

Modeling of heating process

Energetic parameters presented in previous section of the article were determined basing on extreme heat fluxes that were noticed in steady states. In real exploitation conditions of warming systems, energy consumption strongly depends on thermal delay time of building, especially of elements characterized by maximal heat capacitances. External walls and heating floor are characterized by described parameters.

During calculations it was assumed that external wall of analyzed building is composed with two materials of parameters described in Table 1.

Table 1. Material parameters of external wall

Material	Thickness, m	density, kg/m^3	Speciffic heat, J/(kg·K)	Thermal conductivity, W/(m·K)
Constructional (ytong)	0,24	550	840	0,15
Insulating (styrofoam)	0,15	12	1460	0,044

Calculations of heat conduction for external wall of the building were performed with assumption that average ambient temperature was at -10ºC. The external temperature was sinusoidal change (amplitude ±10 ºC) to take into account the daily temperature variations. Internal temperature was at 20ºC and it was constant. The heat wave inside the wall is shown in figure 3. Basing on presented calculations, one can observe that the constructional layer is characterized by larger time delay value. Total time constant for external wall (that is a time required that the disorder has reached the opposite surface) was at 13 h [3].

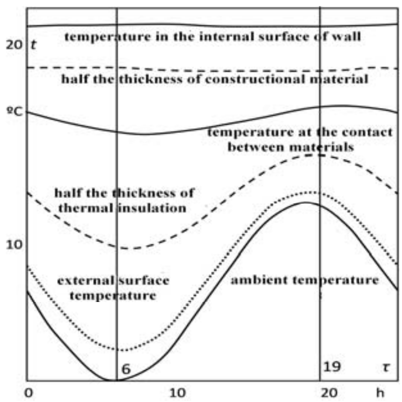

Figure 3. Thermal wave inside external wall

In the figure 4.a the range of daily temperature profiles has been shown. Even when one assumes temperature differences at 20 K, a high value of accumulative energy in constructional material compensates heat flow inside the wall. Basing on this assumption one can calculate required thickness of styrofoam to guarantee that constructional layer will never freeze (dew point). In III and IV climate zones, minimal thick of styrofoam is 7 – 8 cm.

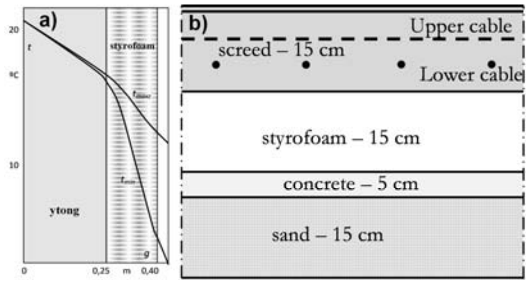

Fig. 4. Daily temperature distribution inside external wall of the building (a) and structure of heating floor (b)

Heating floor of parameters presented in table 2 was analyzed. Two cases for different power distributions were analyzed:

- Single circuit system of power density 37,5 W/m^2. In this case power was generated continuously;

Two circuits system of total power density 90 W/m^2 (lower circuit 30 W/m^2, upper circuit 60 W/m^2). In this case system was powered by 10 hours per day.

Table 2. Material parameters of heating floor

material	γ kg/m^3	c J/(kg·K)	λ W/(m·K)
terracota	2800	920	2,6
screed	1900	840	1,2
styrofoam	12	1460	0,042
concrete	1800	840	0,9
sand	1800	840	0,7

Heat transfer coefficient from external surface of the floor were described by using author's formula (1) and shown in figure 5.

(1) $$\alpha = 6{,}4 \cdot \left(t_p - t_w\right)^{0{,}2}$$

where: t_p i t_w are temperatures of the floor and air in the room.

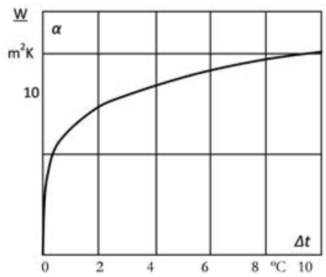

Fig. 5. Heat transfer coefficient from the heating floor

All calculations of single circuit systems were performed by using authors procedures implemented in MathCAD environment. Analysis were done with and without taking into consideration the heat loses to the ground. In the figure 6 the comparison between results are shown. Basing on steady state temperature of heating floor, ,one can deduce that heat flux flowing into the ground direction is small and can be omitted during practical calculations.

Modeling of the case with two heating circuits in the floor was done by using the ANSYS environment. All calculations were performed by using this program because of necessity to include geometrical arrangement of two independent heating cables. The geometrical model, with location of boundary conditions, is shown in figure 7. Due to universal scope of this article, only unitary part of heating floor was analyzed, without conditions connected to finite dimensions of the floor.

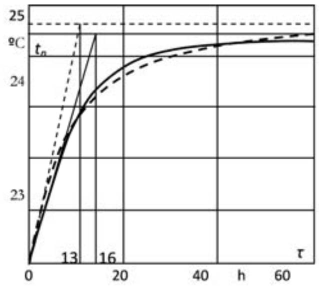

Fig. 6. Heating process of the floor. Continuous line – full model; dashed line – simplified model

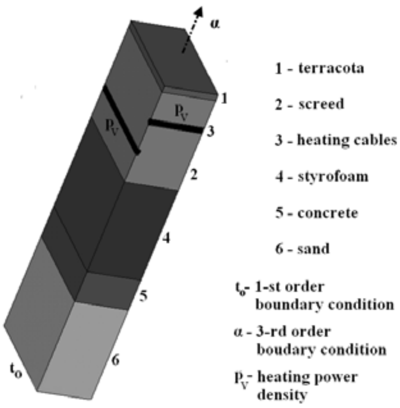

Fig. 7. Geometry of two circuit model with location of boundary conditions

Limitation of the finite elements number was realized by using the symmetry and recurrence of the model. Isothermal surfaces were located in the middle of the distance between each cables. Lower surface of the model (contact between heating floor and the ground) was characterized by uniform and constant temperature value t_0. This assumption was acceptable due to relatively small heat flux in the ground direction and small analysis time, limited to several days [3]. Upper surface of heating floor, from where the heat flux is transferred to the room, was described by third type boundary condition. Temperature dependency of heat transfer coefficient was assumed (1).

During calculations, the heat sources was introduced as homogeneous power density values in heating cables (p_V). Inhomogeneous power density on the surface of heating floor results from different distances between heating cables.

The heterogeneity of heating cables temperature was determined as a function of geometrical arrangement of heating system and heating time. In the figure 8 temperature distribution in all parts of heating floor in the final step of heating process is shown (a). Temperature distribution in the direction of heating cables axis is shown in figure 8.b.

In the case of electrical underfloor heating systems the quantity of minimization of consumed energy and minimization of exploitation costs are different definitions. Analysis of time constants of different parts of the building, it can be shown that G12 tariff can decrease the thermal comfort in comparison to the case when one can use electrical energy anytime (G11 tariff).

The comparison between underfloor heating system exploited by 10 hours per day (power density 90 W/m^2) and the system that was continuously heated (power density was 2,4 times smaller 37,5 W/m^2) were done. The results are shown in figure 9 and table 3, where total temperature differences in cases where heating systems were powered by nominal, 2/3 and 1/3 of the nominal power values are compared.

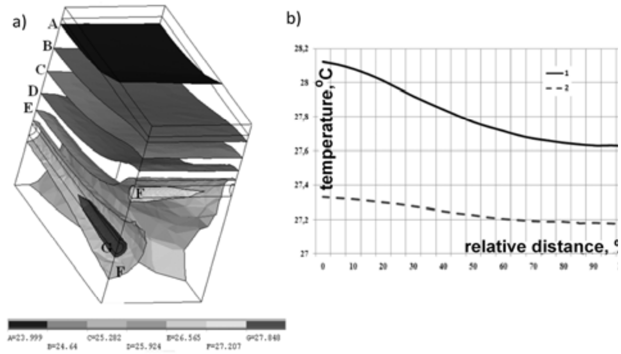

Fig. 8. Isothermal surfaces In the heating floor (a) and temperature distributions as a function of relative length of heating cable: lower (1) and upper (2) heating zone

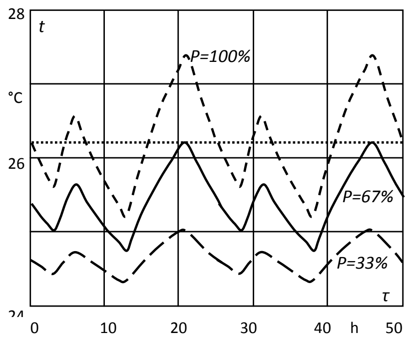

Fig. 9. Temperature differences in two-circuit heating floor explored in G12 tariff

In table 4 the range of surface power densities loss from the heating floor are shown. The power values were calculated for every temperature, as for single as for two circuit heating system.

Table 4. Power values transferred from the heating floor of temperatures shown in table 3.

pe W/m^2	pc_{max} W/m^2	pc_{min} W/m^2
90	65	18,3
60	38,9	10,4
30	15,6	3,5

Heating floor heated only in night tariff is characterized by significant temperature fluctuations in comparison to the case, when it was heated continuously. This fact can affect on thermal comfort inside the building. But in real conditions, maximal energies are used very rarely (fig. 2). Heating times of heating floor depend on thermal loses from heated building and, in most cases, are from 50 to 75% of the full range.

Exemplary power control manner

The time required for increase temperature of 15 cm thick heating floor of 1 K is from 100 to 300 minutes. In practice, cooling times are few times longer. So that, heating floor is the element characterized by asymmetric time constants. This feature is very often used in “casual” warming techniques.

Thermal state of underfloor heating system depends on many different factors. Fulfill of these parameters enables to achieve a appropriate constant temperature inside the building. One of the most important factors is adjustment of heating floor temperature in advance. Forecasting of floor temperature can guarantee that the temperature will be lower and characterized by minimal oscillations. In the next calculations only state when one can use night (cheaper) tariff was analyzed. Characteristic heating interval was chosen and equal to situation, when continuous power was at 20,62 W/m^2. Two heating procedures was compared in the same quantities:

- single circuit system heated between 2:30 – 6 am and 1-3 pm (total power *p3*);
- two-circuit system heated from 10 pm to 0:30 (power *p2* = 2/3 *p3*), 0:30 am – 6 am (power *p1* = 1/3 *p3*) and 1 pm – 3 pm (total power *p3*) (fig. 6).

The results of numerical analysis, temperature characteristics of heating floor temperature, have been shown in figure 10. In the first case, oscillations of floor temperature *t1* have amplitude 2,3°C and in second case – 1,4°C. Lower temperature differences show that optimal case is utility of two-circuit underfloor heating system.

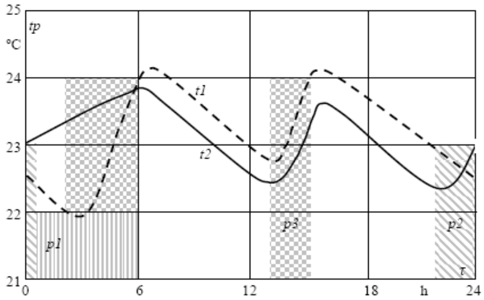

Fig. 10. Heating floor temperature variations for one (*t1*) and two-circuit (*t2*) heating system

In the figure 11 exemplary heating characteristics of two-circuit heating system with continuous power loses *p0* are shown. When the power is on between 1 pm – 3 pm, the heat loses increase. But in the night, power loses decrease because in the morning analyzed building is characterized by minimal temperature. If one take into consideration that external walls of the building have a larger time delay values (in comparison to heating floor), there is possibility to develop the algorithm to better utility of electrical energy in such heating systems [4]. During projecting the underfloor heating systems without analysis of transient states, it is impossible to effective utility of thermal energy, especially converted from electricity. Even when one use advanced control systems that use two temperature sensors (mounted in the internal wall and the heating floor), optimal operating conditions cannot be reached until external weather conditions are not controlled [4, 5].

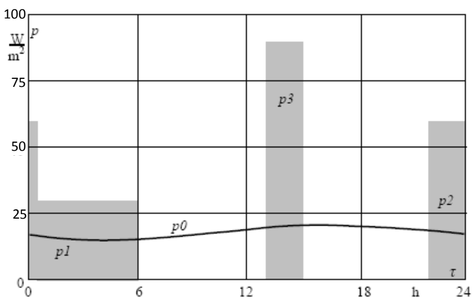

Fig. 11. Power values of underfloor heating system and power loses to the environment (*p0*)

Basing on presented results, one can deduce that in accumulation underfloor heating systems, temperature controller should be replaced with energy controllers. Such controller should operate basing on balancing the energy loosed to the environment (calculated from external temperature and room temperature) and energy delivered to the building from heating floor (calculated from temperature of the floor and room temperature). So that, appropriate operation of underfloor heating system requires to use three temperature sensors. When internal temperatures are measured independently in any room of the building, there is possibility to achieve required temperature values in any room.

Conclusions

In the article basic problems of rational construction and exploitation of different types of underfloor heating systems were analyzed. Transient temperature analysis of basic constructional elements of exemplary building were presented. Two basic cases with single- and two-circuits heating systems were compared in one- and two tariff systems. Different heating and cooling times of heating floor result from daily environmental conditions and maximal temperature of the floor. Comparison between results enable to determine the energetic efficiency of all analyzed cases and to determine most important parameters that have a strong influence on control systems in such class of electrothermal objects. Presented results enable additionally to determine some constructional conditions of two-circuit floor heaters. It was shown that different time constant values of constructional elements and requirements related to thermal comfort, are factors which determine potential better parameters of two-circuit underfloor heating systems. Possibility of precisely and independent control of heating process in all zones enable to control the accumulative energy and decrease the energy consumption of multi-circuit underfloor heating systems. In such class of electrothermal devices temperature controllers should be replaced with energy controllers with possibility of dynamic reaction to the changes in environmental conditions.

Autorzy: *dr inż. Ryszard Niedbała, Politechnika Warszawska, Instytut Elektroenergetyki, ul. Koszykowa 75, 00-662 Warszawa, E-mail: ryszard.niedbala@ien.pw.edu.pl; dr inż. Marcin Wesołowski, Politechnika Warszawska, Instytut Elektroenergetyki, ul. Koszykowa 75, 00-662 Warszawa, E-mail: Marcin.wesolowski@ien.pw.edu.pl*

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