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ANALYSIS OF THERMAL PROPERTIES OF FLOORS IN HEATED BUILDINGS

The article discusses some thermal properties of floors and floorings, such as heat transfer and heat absorption. It was pointed out that there are no specific requirements in the field of heat absorption by floor construction in the Polish building regulations. The property of heat accumulation through the floor not only affects the thermal sensations of the room users, but also affects the heat loss of such a construction. The main objective of the study was to assess the heat absorption capacity of floors and flooring made of various types of wood and compare them with floors finished with natural stone or ceramic tiles. Comparison of the thermal activity of the floor from different types of wood shows some differences that allow to identify types of wood that may be more or less active in these thermal processes. Characteristically, it has also been found to determine a wood floor thickness that is similar for different types of wood, where the properties related to heat accumulation stabilize. In the case of a floor finished with natural stone or with ceramic floor tiles, in contrast to wood, as the thickness of the finishing layer increases, an increase in the activity associated with the accumulation of heat is observed.

Key words: floor, flooring, wood flooring, specific requirements, thermal parameters, heat absorption.

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АНАЛІЗ ТЕПЛОВИХ ВЛАСТИВОСТЕЙ ЕЛЕМЕНТІВ ПІДЛОГ В ОПАЛЮВАНИХ БУДИНКАХ

Розглянуто такі теплові властивості підлог та підлогових покриттів як теплопередача та теплопоглинання. Конструкції підлоги розміщуються на землі, над підвалом або в неопалюваній кімнаті або над проїздом у будівлі або аркаді. Вказано на відсутність детальних вимог щодо проектування адекватної теплової абсорбції підлоговими конструкціями в польських будівельних правилах. Властивість нагромадження тепла через підлогу має величезний вплив на теплові відчуття користувачів опалюваних приміщень. Ці властивості також непрямим шляхом впливають на тепловтрати будівлі в результаті цього фізичного явища. Коли термічна акумуляція підлоги збільшується, користувач намагається покращити свої теплові відчуття, збільшуючи температуру в приміщенні. Цього можна досягти, збільшуючи подачу повітря в приміщення. Це, своєю чергою, може призвести до збільшення втрат тепла через захищення, що аналізуються в статті. Основна мета дослідження полягає в оцінці теплопоглинальної здатності підлоги та підлогового покриття, виготовленого з різних видів деревини, а також порівняння її з верхнім шаром підлоги з натурального каменю або

керамічної плитки. Порівняння теплової активності підлоги з різними типами деревини показує деякі відмінності, які дають змогу визначати типи деревини, які можуть бути більш-менш активними в цих термічних процесах. Характерно також, що товщина дерев'яної підлоги в певний момент часу, коли процес поглинання тепла практично стабілізується, дуже подібна для різних типів деревини. Виявлено також, що підлогове покриття з натурального каменю або керамічної плитки, на відміну від деревини, свідчить про збільшення товщини обробного шару та збільшення накопиченням тепла.

Ключові слова: підлога, підлогове покриття, настили, паркети, конкретні вимоги, теплові параметри, поглинання тепла.

Introduction. Thermal properties of floors and their outer layer, termed flooring, can be considered in two contexts. One of them is the process of heat transfer through these structures and the related heat loss from the building. The other is heat processes connected with thermal sensations of the building's users, including activity in terms of thermal accumulation of these structures. Although the former process and the related properties have been paid much attention in the literature on building physics and building energy efficiency, the interest with the latter seems to be marginal. This is undoubtedly correlated with solving the problem of thermal insulation and energy properties of a building and its components in the form of specific technical building guidelines. However, these regulations do not define the properties of the structure in terms of thermal sensations or thermal comfort of the users. The paper discusses and comments on basic properties of floors and flooring such as thermal permeability and thermal absorption. The major focus of the study was on thermal absorption in wood flooring. With respect to thermal permeability, this phenomenon is affected by all layers of the floor, whereas the processes of heat activity can be affected by one, two or three layers of the floor from the top. The greatest effect is always from the first (outer) layer. Therefore, in order to ensure the clarity of the problems presented in this study, this is referred in the case of thermal conductivity to the properties of the floor and its load-bearing structure and, in the case of thermal accumulation, to flooring properties (although, as observed above, flooring thermal activity is also affected by floor layers under the flooring.

Basic thermal parameters of the floor. The basic parameter that characterizes thermal insulation of structural barriers, including floor and its structural layer, is thermal transmittance U, W/(m^{2}K). The value of this coefficient and heat loss in this floor depends first and foremost on thermal resistance of individual layers and thermal resistance on the surface of the floor. In the case of floor on the ground, the U value is affected by thermal resistance of the ground layer, with particular focus on the edge zone of the floor and, in the structures of floors over e. g. underpasses or arcades, thermal resistance of the thermal insulation layer attached from the bottom to this floor. According to current building regulations and those expected to be changed in the nearest future [1], the required level of thermal insulation of the structures with floor and flooring, is presented in Table 1.

Table 1

Comparison of the required value of thermal transmittance U_{Cmax} for floors with flooring [1] depending on computational air temperature in rooms t_i

Year of the entry into force of the provision	Required value of thermal transmittance, U_{Cmax}		
	$t_i \geq 16$ °C	$8 \leq t_i \leq 16$ °C	$t_i < 8$ °C
	W/(m^2 K)		
	The floor on passing through		
2017	0,18	0,30	0,70
2021	0,15	0,30	0,70
	The floor above an unheated room and enclosed space underfloor		
2017-2012	0,25	0,30	1,00
	The floor on the ground		
2017–2012	0,30	1,20	1,50

According to the ordinance [1], design of barriers should also take into consideration another requirements that refers to thermal insulation properties. In the residential buildings, collective residential buildings, public utility buildings as well as production buildings, warehouses and farm buildings, a thermal insulation layer with thermal resistance of 2.0 m^2K/W should be applied on the perimeter of the floor on the ground in the heated room i. e. in the place of connection with the external walls. The ordinance does not contain the data about the width of the insulation zone. With regard to the guidelines of the previous thermal standard, the width of the insulation zone on the floor level or in the vertical line of the foundation walls or basement walls not lower than 1m can be adopted.

Thermal resistance of the floors layers and thermal transmittance for the floors in contact with the air should be calculated according to the standard PN-EN ISO 6946:2008 Building components and building elements. Thermal resistance and thermal transmittance. Calculation method. Furthermore, thermal transmittance of the barriers in contact with the ground should be calculated using the specific method according to PN-EN ISO 13370: Thermal performance of buildings Heat transfer via the ground. Calculation methods. In the case of a flooring, where people go without shoes (swimming pools, gyms, bathrooms, etc.) is a very important issue. Based on the theory of heat flow values the optimal surface temperature of the various kinds of floorings have been determined (Tab. 2).

Table 2

The optimum temperature of the surface in contact with the floor bare foot [2, 3]

Material of flooring	Optimum surface temperature a contact time of the foot to the flooring		The recommended range of surface temperatures flooring
	1 min	10 min	
	^{o}C		
Carpeted	21,0	24,5	21,0–28,0
Cork (5 mm)	24,0	26,0	23,0–28,0
Beech wood	25,0	26,0	22,5–28,0
Oak wood	26,0	26,0	24,5–28,0
Wood	26,5	25,5	–
PVC (2 mm)	28,0; 29,0	27,0; 27,5	25,5–28,0
Linoleum on wood	28,0	26,0	24,0–28,0
Gas concrete	29,0	27,0	26,0–28,5
Concrete screed	28,5	27,0	26,0–28,5
Marble	30,0	29,0	–

Floorings used by people wearing shoes, regardless of the material does not usually affect the feel associated with the local thermal comfort. In this case, it is recommended that the optimum temperature of the flooring for a person in a seated position is 25 °C and standing or walking is 23 °C. Generally, with underfloor heating the average temperature of the flooring should not exceed 29 °C. The exception is the boundary zone along the outer walls of the room and bathrooms [2]. For the feelings associated with the barefoot contact with wooden floorings much lower value for optimal comfort surface temperature is achieved than most other materials.

Setting goals and objectives of research. Thermal activity of the structural barrier is connected with the phenomenon of absorption and release of heat, which occurs under conditions of dynamic heat effect on building structures. One of such processes is mutual effect of floor structure, with particular focus on the effect of flooring on human foot and the related thermal sensations.

This problem has been paid relatively little attention in the technical literature, although the process substantially affects sensations connected with the comfort of building use. Flooring thermal absorption capability, which characterizes capability of the structure to transfer heat to human feet, depends on the design and, in particular, the type of material used for the surface layer of floors. Thermal-absorption properties of flooring, including wood flooring made from various types of wood and comparison of these properties to other materials will be discussed later in the study. Thermal activity of a building barrier is mainly determined by the materials used, with particular focus on the following physical parameters of these materials: specific heat c_p, thermal conductivity l, thermal diffusivity a, thermal absorption s_{24}.

Thermal diffusivity a expresses the speed at which temperature in the material is evenly distributed. Therefore, this coefficient is used during e. g. analysis of unsteady thermal processes that occur in the structures with variable thermal effect. With higher values of thermal diffusivity a during heating or cooling of the material, the temperature is equalized in various points at a faster rate (leading to stabilization of thermal conditions). Wood is the material with especially good properties. It is characterized by several-time higher values of thermal diffusivity a compared to many other building materials, with particular focus on structural materials, which substantially affects good thermal stability of wooden structures. This property is slightly deteriorated only in the places where heat is transferred along the wood grain as a result of the increase in the value of thermal conductivity. Thermal diffusivity of wood decreases with its humidity.

Thermal absorption is another parameter used during analysis of unsteady thermal conditions that occur in building structures. It characterizes material ability to absorb heat during temperature fluctuations on the material surface. Therefore, the increase in thermal absorption s_{24} leads to the increase in the intensity of the process. Another parameter connected with the phenomenon of thermal absorption is thermal accumulation b, measured in W/(m^2 K) or thermal accumulation B, measured in Ws$^{1/2}$/(m^{2}K). They are used e. g. during evaluation of upper layers of flooring to receive heat from human feet.

Floors, especially with wood flooring, are characterized by very good properties of thermal absorption since wood thermal activity coefficient is one of the lowest among the materials used in this structural component. For the pine wood, it ranges from 450 to 480 Ws$^{1/2}$/(m^2 K) for heat flow transversely to grains and from 700 to 730 Ws$^{1/2}$/(m^2 K) for heat flow along the grains. Furthermore, for the oak wood, this coefficient is higher, ranging from 600 to 680 Ws$^{1/2}$/(m^2 K) for heat flow occurring transversely to grains and from 800 to 900 Ws$^{1/2}$/(m^2 K) for heat flow along the grains. Wood flooring is considered as warm flooring i. e. if the foot is in contact with the floor, after initial sensation of cold, the temperature in the place of contact gradually increases.

Floors finished with wood flooring or cork flooring are numbered among those which allow for obtaining an optimal comfort of surface temperature for the sensation of the contact of bare foot with the surface, which is much lower than other finishing materials [3]. The literature that describes properties of flooring and floor contains the data concerning the requirements and recommendations connected with thermal accumulation of flooring, see Tab. 3 [4] and Tab. 4 [5]. The manual [5] contains classification of flooring with respect to thermal activity (thermal sensations) measured with thermal accumulation B. The specific ranges of thermal activity correspond to the type of thermal sensation: to 350 – warm; (350÷700) – sufficient; (700÷1400) – too cool; over 1400 – cold.

Table 3

Requirements concerning thermal accumulation of flooring according to [4]

Type of building and the use of rooms		Thermal accumulation of flooring, *b* W/(m^2 K)
II	Residential buildings, hospitals, health centers, sanatoriums, orphanages, care facilities, nursery schools, preschools, schools etc.	≤ 12
III	Public utility buildings not listed in point 1, surfaces in the heated commercial buildings, industrial buildings etc., with places for permanent low-intensity exercise work.	≤ 14
IIII	Surfaces in the rooms of heated commercial buildings and industrial buildings with places for permanent medium-intensity exercise work.	≤ 17

Assumptions and methodology for determination of the thermal accumulation of flooring *b* and results for calculations for various material solutions using wood flooring were discussed in the study [6].

Table 4

Requirements in terms of thermal accumulation of floors with assumption of 10-minute contact of foot with the floor according to [5]

Type of building and rooms		Decrease in foot temperature over the period of 10-minute contact with floor, Δt_{10}	Coefficient of thermal accumulation, B
		K	W $s^{1/2}/(m^2$ K)
1	Public utility buildings, rooms with higher sanitary and hygienic requirements, e. g. rooms in nursery schools, preschools, hospitals, operating rooms, intensive care rooms, rooms in orphanages, social care facilities etc. Residential buildings, bathrooms	< 3.8	≤ 348
2	Residential buildings, rooms, kitchens. Schools, classes, gyms. Health centers, surgeries. Hospitals, wards, surgeries. Other: office rooms and studios, hotel rooms, cinemas, concert halls, restaurants etc.	3.81 – 5.50	348 – 585
3	Residential buildings, hallways, halls Schools, corridors. Health centers and hospitals, waiting rooms. Other: corridors with waiting rooms in various facilities warehouses with constant operation, museums, exhibition rooms, dancing rooms, groceries etc.	5.51 – 6.00	585 – 845
4	Other, not listed in Points 1 – 3, without requirements	> 6.90	> 845

First methodology to determine thermal accumulation of floor, measured with *b* parameter was presented in the study [4].

The calculated value of the heat absorption index of the floor surface is determined as follows:

1. If the floor covering (the first layer of a design of a floor) has thermal inertia $D_1 = R_1\ s_1 \geq 0{,}50$, that the coefficient of heat absorption of the floor surface should be defined on

$$b = u_1 = 2\ s_1, \quad s_1 = 0{,}0085(l_1\ c_{w1}\ r_1)^{1/2} \tag{1}$$

where D_1 – thermal inertia index of the first layer; R_1 – thermal resistance of the first layer, m^2 K/W; s_1 – heat absorption coefficient of the first layer material, W/(m^2 K); l_1 – conductivity of the first layer material, W/(m K); c_{w1} – specific heat capacity of the first layer material, J/(kg K); r_1 – material density of the first layer material, kg/m^3.

2. If the *n* layers floor ($n \geq 1$) have a total thermal inertia $D_1 + D_2 + ... + D_n < 0{,}50$, but the thermal inertia of the (*n*+1) layers $D_1 + D_2 + ... + D_{n+1} \geq 0{,}50$, the coefficient of heat absorption of the floor surface should be determined sequentially by calculating the heat absorption of the surfaces of the layers of the structure, starting from *n* to the 1st layer:

for *n* layer - according to the formula

$$u_n = (2\ R_n\ s_n^2 + s_{n+1})/(0{,}5 + R_n\ s_{n+1}), \tag{2}$$

where $D_1, D_2, ... D_n$ – thermal inertia index of the 1, 2,... *n* layer; u_n – coefficient of heat absorption through the surface layer, W/(m^2 K); $R_1, R_2, ... R_n$ – thermal resistance of the 1, 2,... *n* layer, m^2 K/W; $s_1, s_2, ... s_n$ – heat absorption coefficient of the 1, 2,... *n* layer material, W/(m^2 K); for the *i*-th layer ($i = n - 1$, $i = n - 2$,... 1) - by the formula,

$$u_i = (4\ R_i\ s_i^2 + u_{i+1})/(1 + R_i\ u_{i+1}) \tag{3}$$

Another methodology to determine thermal accumulation of floor, measured with *B* parameter was presented in the study [2]. The first step in the computation procedure is to evaluate the depth of thermal effect of the floor structure on the foot in contact with this structure. Typically, three cases of floors and flooring are possible:

1. Single-layer floor, for which the following condition is met

$$d_1 > 42{,}4\sqrt{a_1} \tag{4}$$

where d_1 – thickness of the first layer, m; a_1 – thermal diffusivity for the material of the first layer of the floor, m^2/s.

In this situation, thermal accumulation is:

$$B = B_1 = \sqrt{l_1\, c_{p1}\, r_1} \quad .$$

2. Two-layer floor, for which the condition for the single-layer floor is not fulfilled, but the following conditions is met

$$\frac{d_1^2}{a_1\, t} + \frac{d_2^2}{a_2\, t} \geq 3{,}0 \tag{5}$$

and thermal activity is affected by the first and the second layer.

In this case, thermal accumulation is:

$$B = B_1\,(1 + K_{1,2}) \quad ; \quad K_{1,2} = f\left(\frac{B_2}{B_1}, \frac{d_1^2}{a_1 t}\right) \tag{6}$$

3. Three-layer floor, for which the conditions for the two-layer floor is not met, that is

$$\frac{d_1^2}{a_1\, t} + \frac{d_2^2}{a_2\, t} < 3{,}0 \tag{7}$$

I this situation, thermal accumulation is:

$$B = B_1\,(1 + K_{1,2,3})$$

$$K_{1,2,3} = f\left(\frac{B_{2,3}}{B_1}, \frac{d_1^2}{a_1 t}\right); \quad B_{2,3} = B_2\,(1 + K_{2,3}) \quad ; \quad K_{2,3} = f\left(\frac{B_3}{B_2}, \frac{d_2^2}{a_2 t}\right)$$

In all the above relationships:

$K_{1,2}$, $K_{1,2,3}$ – dimensionless coefficients that determine the effect of the second layer on thermal activity of the first; and effect of the second and third layer on thermal activity of the first; values adopted from the tables according to [5]; $B_1 = \sqrt{l_1\, c_{p1}\, r_1}$, $B_2 = \sqrt{l_2\, c_{p2}\, r_2}$ – coefficients of thermal accumulation of the material of the first and second layer of floor, Ws$^{1/2}$/(m^2 K); t – computational time of foot contact with the floor, 720 s.

Research methodology. Analysis of thermal activity of the floors was carried out using the calculation method presented in the previous item. Ten different types of wood were adopted (Table 5), with physical parameters adopted from publications [7, 8, 9]. Table 5 also contains technical parameters of ceramic, marble and other materials used in the layers under the floor. Wood flooring was adopted as lying on a concrete base layer with thickness of 5 cm. The range of thickness of the wood layer adopted for calculations range from 5 and 30 mm. Thickness of the wooden panels ranged from 6 to 14 mm, ceramic tiles from 6 to 30 mm and marble slabs from 15 to 45 mm.

This result slightly differs from the value obtained in calculations presented in the study [6], where thermal accumulation b, W/(m^{2}K), adopts a constant value for the thickness of wooden layer of flooring at the level of from 20 to 22 mm.

The calculations show that thermal accumulation of flooring decreases with thickness, which reflects declining thermal activity of the structure. Therefore, the increase in the thickness of wood layer improves properties connected with thermal absorption from human foot by the floor structure. The diagram also clearly shows that thermal activity of the wooden flooring structure stabilizes at the level of around 18 mm.

With greater values of wooden layer thickness, thermal accumulation coefficient maintains at a steady level for all the types of wood.

Table 5

Types of wood and other materials and their physical parameters used in calculations

Type of wood or other material floor		Desity	Thermal conductivity	Specific heat capacity	Thermal absorption	Coefficient of thermal accumulation
		ρ	λ	c_p	s_{24}	B
		kg/m^3	W/(m K)	J/(kg K)	W/(m^2 K)	W s$^{1/2}$/(m^2 K)
1	Beech	720	0,16	2000	4,33	509,1
2	Birch	640	0,19		4,19	493,2
3	Oak	680	0,19		4,32	508,3
4	Ash	710	0,17		4,18	491,3
5	Fir	440	0,12		2,76	325,0
6	Maple	650	0,16		3,88	456,1
7	Larch	580	0,15		3,55	417,1
8	Pine	510	0,13		3,10	364,1
9	Spruce	460	0,12		2,82	332,3
10	Poplar	440	0,13		2,87	338,2
11	Concrete	1800	1,15	1000	12,23	1438,8
12	Marble	2000	2,50	1000	12,23	2236,1
13	Ceramic tiles	2300	1,30	840	13,47	1584,4
14	Wood panels	700	0,18	2000	4,27	502,0
15	PE foam	375	0,35	2300	4,00	470,5

Result and discussion. Results of calculations of thermal accumulation *b* of wood flooring are presented in the diagram (Fig. 1).

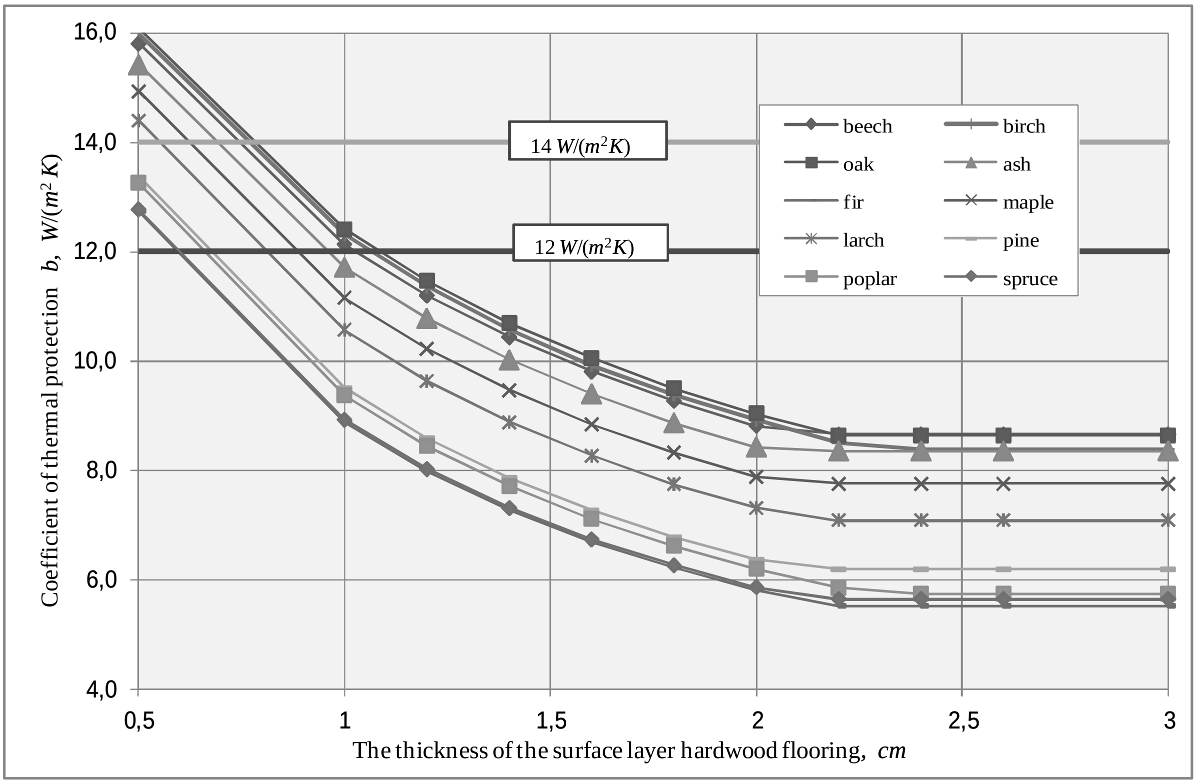

Fig. 1. Character of change of the thermal accumulation of flooring b wooden floors, depending on the thickness of the layer of wood

The most beneficial flooring in terms of thermal accumulation were those made from fir, spruce and poplar wood. Flooring made from these types of wood applied over a concrete base layer with thickness of over 16 mm meet the requirements for the first group of rooms. Other types of wood allow for meeting the requirements for the rooms from the second group, with thickness of wooden layer of over 10–14 mm.

Thermal properties of wood flooring were compared with parameters obtained by floors finished with other materials (Tab. 4), including marble slabs and ceramic tiles on concrete base layer and wood panels on the polyethylene foam and concrete layers.

Comparison of thermal accumulation of the analyzed flooring structures is presented in the diagram (Fig. 2). The profile of the line *B* shows that in the structures of heavy flooring finished with natural stone or ceramic tiles, unlike the structure of wood flooring, deterioration of properties connected with thermal accumulation can be observed with the increase in thickness of surface finish layer. Thermal activity of this flooring is increasing and the structure of flooring made of marble slabs is more active. These structures can be numbered among those which meet only the requirements of the fourth class (Tab. 5).

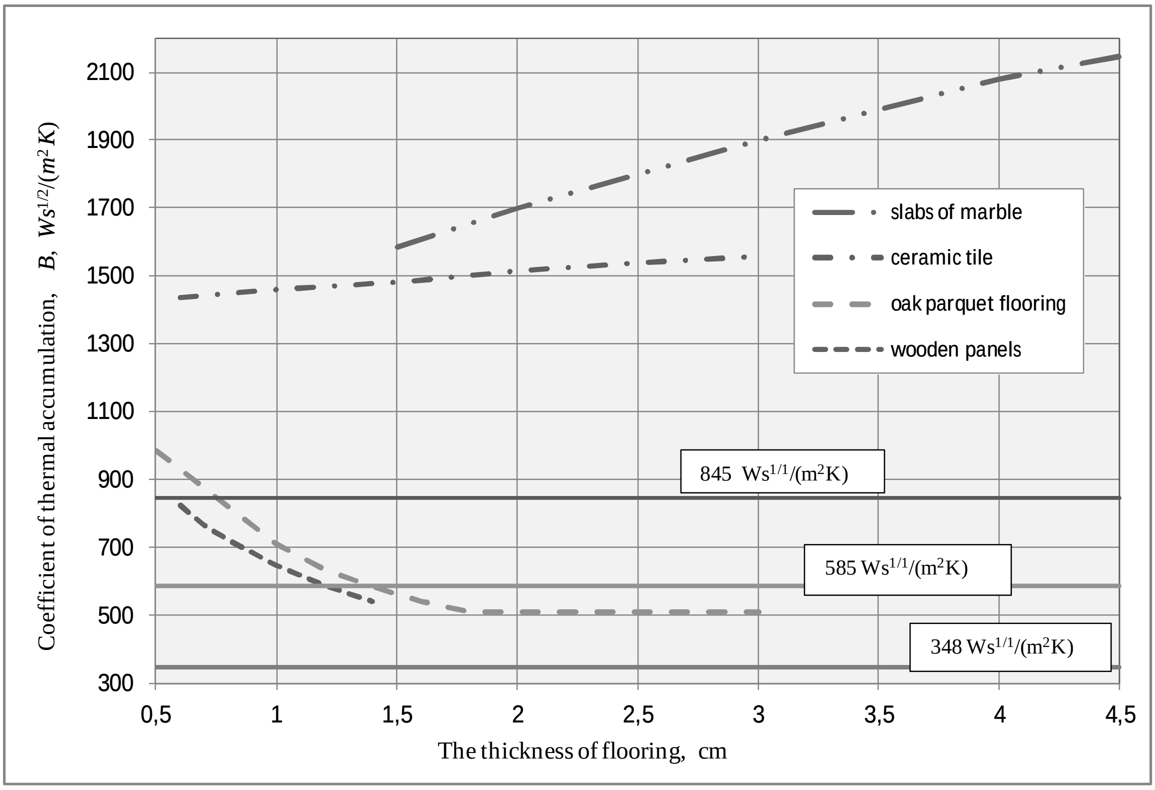

Fig. 2. Character of change of the coefficient of thermal accumulation B floors of different construction depending on the thickness of the surface layer

Furthermore, flooring made of wood panels on the polyethylene foam with thickness of 5 mm and concrete layer with 4 cm yielded positive results. The coefficient *B* for this floor was lower, which indicates lower abilities for thermal absorption compared to the flooring made from oak wood.

Conclusion. Two groups can be emphasized among the parameters that characterize floors and flooring: one connected with processes of thermal transmittance and the other connected with thermal accumulation properties. The increase in thermal insulation leads to a substantial increase in the temperature on the surface of flooring. This is essential to the level of effective temperature and conditions for preventing from mold growth and surface condensation of vapor. Comparison of thermal activity of flooring made from different types of wood shows certain differences that allow for identification of types of wood which are more or less active in these terms. The occurrence of a specific boundary thickness of the wooden floor seems to be characteristic, with this thickness similar for different types of wood, over which properties connected with thermal accumulation are stabilized. The most beneficial in terms of the properties studied is flooring made of types of wood which are popular for flooring, i. e. fir, spruce, poplar and pine wood. The least beneficial is the use of flooring made of oak wood and beech wood for such structures. In the flooring finished with natural stone or ceramic tiles, unlike the structure of wood flooring, deterioration of properties connected with thermal accumulation can be observed with the increase in thickness of the finish layer.

References

1. Min. infrastruktury i rozwoju (2015) Obwieszczenie Ministra Infrastruktury z dnia 17 lipca 2015r. w sprawie ogłoszenia jednolitego tekstu rozporządzenia Ministra Infrastruktury w sprawie warunków technicznych, jakim powinny odpowiadać budynki i ich usytuowanie. Dz. U. 1422/2015, Warszawa, p. 118. 2. Bašta, J. (2010), Velkoplošné sálavé vytápění - podlahové, stěnové, stropní vytápění a chlazení. Grada, Praha. 3. Budownictwo ogólne Vol.2 Fizyka budowli (2017), edited by P. Klemm. Arkady, Warszawa. 4. Jeremkin A. I., Koroljewa T. I. (2000), Teplovoj režim zdanij. IASV, Moskva. 5. Řehánek J. (2002), Tepelná akumulace budov. Informačni centrum ČKAIT, Praha. 6. Ujma A. (2009), Ciepłochłonność posadzek drewnianych, Izolacje R.14 No. 9, p. 48–51. 7. Pióro P. (2018) Układanie parkietów na posadzkach z ogrzewaniem podłogowym. http://lakiery. pl/component/content/article/5-porady-eksperta/37-parkiet-na-ogrzewaniu-podlogowym. html (accessed 28 October 2018). 8 Kozakiewicz P. (2006), Fizyka drewna w teorii i zadaniach. Warszawa. 9. The Encyclopedia of Wood, (2007), Forest Products Laboratory, US Dept. of Agriculture, Skyhorse Publishing Inc, New York.