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To cite this article: Yu V Tsapko *et al* 2020 *IOP Conf. Ser.: Mater. Sci. Eng.* **907** 012057

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Modeling of thermal conductivity of reed products

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Abstract. The present work researches processes of heat transfer by samples of mats manufactured from reed. Due to the unique properties of the reed, such as medium density, low thermal conductivity, relatively high weather resistance, high chemical resistance, possibility to produce parts on-site, cost-effectiveness and others, reed products are widely used in building construction despite the high rate of development of new technologies. The mechanisms of heat insulation in the result of energy transfer through the material are established, which makes it possible to influence this process. It is proven, that the mechanisms are conditioned upon the increased porosity of the material. Thus, decreasing volume weight results in decreasing thermal conductivity, and vice versa. The simulation of the heat transfer process with the flameproof coating is carried out, the dependencies of the thermophysical coefficients on the temperature are determined. Based on the obtained dependencies, the coefficient of thermal conductivity for the products made of dry pine wood is calculated and makes 0.056 W / (m · K). Features of slowing down the process of heat transfer to material made of wood wool and glue binding agent with the formation of pores were studied. This is explained by the fact that there is no movement of air in large pores, accompanied by heat transfer. Thus, there are grounds to argue for the possibility of directed regulation of the processes of the formation of thermal insulation products using the reeds characterized by voids in the stems.

1. Introduction

Reed belongs to the group of organic heat-insulating materials and has quite many unique properties, such as low volume weight, low thermal conductivity, relatively high weather resistance, high strength, and elasticity.

Reed products are widely used in low-height housing construction. Reed slabs are used mainly for the construction of walls, partitions, floors, and roofs, that are protected by the heat-insulating and sound-proof material. Due to the tubular structure of the stem, the reeds have low weight and poor thermal conductivity. According to the heat-insulating properties, walls made from the 10 cm thick reeds, plastered on both sides, corresponding to the brick walls with 2 bricks width. Due to the presence of flint deposits in the cells of reed, the reed is exposed to decomposition less than wood. Slabs made from the pressed reed do not burn open flames under the influence of fire but only smolder. Low volume weight of the reed allows the manufacturing of slabs, fascines, and mats used as a wall building material,



as well as for filling of the inter-floor ceilings, as overlapping and roofing material. Production of construction products from reed can be organized easily and with low expenses in places where reed grows. The reed nodes are thickened joint rings, which are located along the stem at a distance of 15-20 cm from each other. There are partitions inside the rings that do not leak air and water. Such a structure of the reeds causes a low thermal conductivity and sufficient strength of products made from reeds.

Thus, the use of reed products, especially in construction, requires the determination of certain properties, in particular, the thermophysical characteristics necessary for the design and manufacture of heat-insulating products. This explains the necessity of research in this area.

2. Analysis of recent research and publications

In recent years, among the works devoted to the use of vegetable raw materials in construction, the works directed to the development of panel slabs for the production of heat-insulating constructions and wooden wall panels are known [1, 2]. The technologies are based on the pressing of a mixture of vegetable fibers with mineral additives, using various natural materials (asbestos, mica, basalt) mixed with hydrophobic components [3, 4]. In the works [5], the impact of the amount of vegetable fiber (flax fiber – cotton fiber) on the density and elasticity of the materials obtained by aeration sedimentation was studied. Also, the effect of the binding agent on the properties of flexible heat-insulating materials was researched, but the question concerning the thermal conductivity that decreases the quality of the gained results remains unanswered.

In the works [6], the thermal conductivity of insulating wooden and fiber slabs was evaluated at different temperatures and relative humidity. It was established that accurate datasets on the thermal behavior of insulation materials are crucial in numerical modeling approaches that will improve the correct construction of enclosure structures. However, it is not specified how the thermal conductivity was determined. In the works [7], data on production technology, thermophysical properties of material made from hemp and gypsum binding agent are presented and the possibility of its use as a heat-insulating material is shown. But the issue of the combined effect of the components on heat-insulation remains uncovered. Materials, listed in the works [8], are manufactured on the base of basalt fiber and are characterized by high heat-insulating properties. But the technology of its production, the method of determination of this value and the volumetric characteristics are not described.

In the direction of these studies [9], a mathematical model was proposed describing the dynamics of the heat transfer and conservation properties on a fibrous insulation coating, taking into account the "internal" features of the insulator (granularity and porosity of fibrous insulation made from a mixture of natural and synthetic fibers). However, this model does not take into account how the change in pore shape affects the heat transfer to the structure itself.

The heat-insulating materials manufactured from the mixed carpet waste with the solution of a colemanite ore, one of the boron minerals and the solution with added colemanite waste [10] were also studied. It is shown that the established optimal ratios enable the correction of the content of the components to ensure the heat-insulation process. In addition to gaining knowledge about permanent panels, the understanding of non-uniform plates has been improved due to the identification of two major components [11]. This knowledge of the internal microstructure of a slab made of the bark of wood allowed to create a numerical model for thermal conductivity based on methods of finite differences.

Thus, the use of reeds in building construction requires the determination of certain properties, especially the thermophysical characteristics necessary for the manufacture of heat insulation products, which is the subject of this works.

3. The purpose of this work

The purpose of this work is to determine the thermophysical characteristics of reed construction products for the determination of conditions of thermal conductivity suppression of building construction.

4. Materials and methods of research

For the study of thermal conductivity, the reed samples of average sizes were used: 10 mm in diameter and 310 mm in height, bound in $150 \times 150 \times 25$ mm mats (Figure 1).



Figure 1. Model sample of a heat-insulating mat from reeds.

To obtain the values of the thermal conductivity of vegetable raw materials, special equipment was developed and manufactured; a flat electric heater was used to simulate a low-calorie heat source (Figure 2).

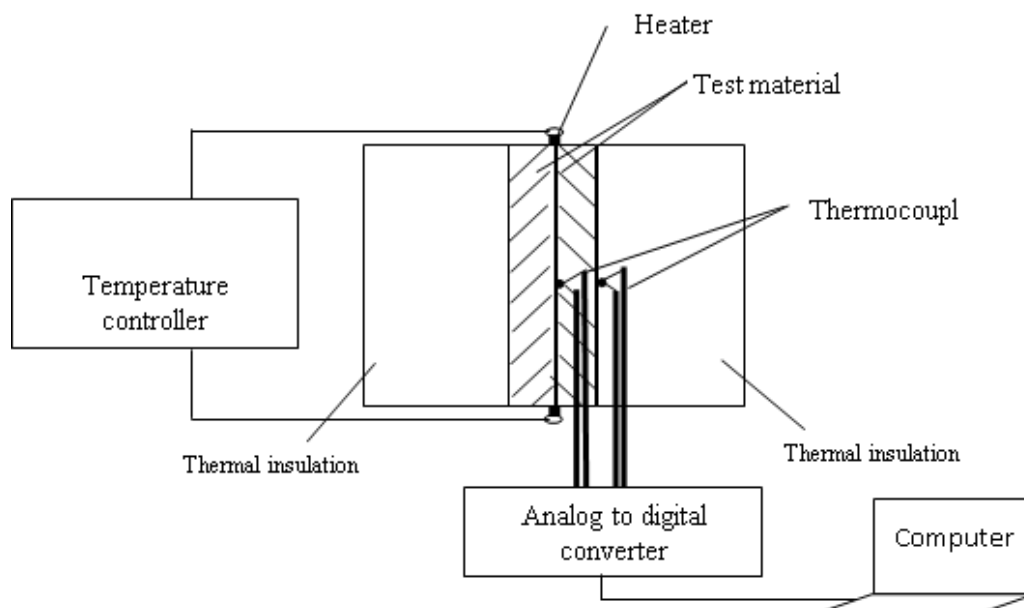


Figure 2. Device for research of thermal conductivity of the mat made from the reeds.

The heater was manufactured as follows: a nichrome wire with a resistance of 83 ohms was applied to a 100×100 mm electrical insulation plate, a tension of 24.5 volts was supplied to it. The heater was placed in a heat-insulating plate to minimize the heat losses around the perimeter.

A heater with a thermocouple was placed between the test plates made of the reed, and a control thermocouple was placed on the reverse wall of the reed sample. The sample was fixed so that the end of the thermocouple was pressed against the inner surface of the sample. The electric heating was switched on, the temperature of the heater and the one on the back surface of the sample were measured.

When the temperature reached 70°C , the heater was switched off, and the temperature continued to be measured to the value of $0,5T_{max}$ on the reverse surface of the sample. The measured values determined the heat-insulation properties of the sample mat made from the reeds.

The criterion for determining the thermal conductivity of the reed under thermal action is the value equal to $0.5T_{max}$ on the reverse surface of the mat sample.

5. Modeling of the heat transfer parameters for reed construction products.

Studies on the modeling process of thermal conductivity of the mat made from the reeds under thermal action were performed using fundamental principles of the mathematical physics [12].

A method for solving the thermal conductivity problem for a plate is proposed to determine the thermophysical characteristics of the reed mat. A semi-infinite body at temperature T_0 is given. One of the surfaces is heated by a constant heat flow $Q = \text{Const}$. The temperature changes in one direction (Figure 2). Find the temperature distribution in this direction at any given time.

The differential equation describing this process looks as follows:

$$\frac{\partial^2 T(x, \tau)}{\partial x^2} - \frac{1}{\varphi^2} \frac{\partial T(x, \tau)}{\partial \tau} = 0, \quad (\tau > 0; 0 < x < \infty), \tag{1}$$

with the following initial and boundary conditions:

$$T(x, 0) = T_0, \tag{2}$$

$$\lambda \frac{\partial T(x, \tau)}{\partial x} = q = \text{const}, \tag{3}$$

$$T(\infty, \tau) = 0, \tag{4}$$

$$\frac{\partial T(\infty, \tau)}{\partial x} = 0 \tag{5}$$

where is the T_0 – initial temperature of the reed, °C; $T(x, \tau)$ – temperature pattern of the mat made from the reed at points x at time τ , °C; $\varphi = \sqrt{a}$; a – coefficient of temperature conductivity of the mat made from the reed, m^2/s ; τ – residence time of the sample in a high-temperature environment, s; q – heat flow, W/m^2 ; λ – coefficient of thermal conductivity of the reed mat, $\text{W}/(\text{m} \cdot \text{°C})$.

The solution of the equation (1) with the initial and boundary conditions (2) – (5) is given in the works [16] as follows:

$$T(x, \tau) - T_0 = \frac{2 \cdot q \cdot \varphi \cdot \sqrt{\tau}}{\lambda} \text{ierfc} \frac{x}{2\varphi \cdot \sqrt{\tau}}, \tag{6}$$

where is the

$$\text{ierfc} x = \int_x^\infty \text{erfc} \xi d\xi = \frac{1}{\sqrt{\pi}} e^{-x^2} - x \text{erfc} x - \text{error integral}. \tag{7}$$

If the temperature is measured in the plane of the heater ($x=0$), the equation below follows from (6):

$$T(0, \tau) - T_0 = \frac{2 \cdot q \cdot \varphi \cdot \sqrt{\tau}}{\lambda \cdot \sqrt{\pi}}, \tag{8}$$

as the right part of the equation (7) by $x=0$ makes $\pi^{-0.5}$.

We denote the relation as an equation:

$$\frac{\lambda}{\varphi} = b, \quad (9)$$

where is the b – coefficient of thermal activity, that characterizes the product's thermal capacity, $W \cdot s^{1/2} / (M^2 \cdot K)$.

We introduce the solution (9) into (8) and obtain

$$T(0, \tau) - T_0 = \frac{2 \cdot q \cdot \sqrt{\tau}}{b \cdot \sqrt{\pi}}. \quad (10)$$

The function (10), in the $\tau^{0.5} = f(T - T_0)$ coordinate system, is a straight line passing through the origin of the coordinates with the following tangent of the angle of slope:

$$\operatorname{tg} \alpha = \frac{b \cdot \sqrt{\pi}}{2q}. \quad (11)$$

The equation for calculation of the coefficient of activity follows from the function (11):

$$b = \frac{2q \cdot \sqrt{\tau}}{\sqrt{\pi} \cdot (T(0, \tau) - T_0)}. \quad (12)$$

As the function (12) shows, the maximum value of the coefficient of the thermal activity is possible at the value $x=0$, which means at the largest value of the heating device temperature.

To ensure the same heat quantity for every experiment, it is necessary to provide constant resistance of the electric heater, tension, supplied to this heater, and heat duration. The heat flow density of the heater is equal to:

$$q = \frac{U^2}{R \cdot 2S} = \frac{P}{2S}, \quad (13)$$

where is the R , U , S – are values of resistance, tension and contact area of the heater.

The coefficient of thermal conductivity is determined by the delay time; for different moments of time τ_1 and τ_2 with the condition $\tau_2 > \tau_1$ it can be written as the equality between equation (6) and (8):

$$\frac{2 \cdot q \cdot \varphi \cdot \sqrt{\tau_1}}{\lambda \cdot \sqrt{\pi}} = \frac{2 \cdot q \cdot \varphi \cdot \sqrt{\tau_2}}{\lambda} \operatorname{ierfc} \frac{x}{2\varphi \cdot \sqrt{\tau_2}}. \quad (14)$$

After transformations we get the following function:

$$\frac{\sqrt{\tau_1}}{\sqrt{\tau_2} \cdot \sqrt{\pi}} = \operatorname{ierfc} \frac{x}{2\varphi \cdot \sqrt{\tau_2}}. \quad (15)$$

The values of the left side of the equation are determined using the formula (15), which includes the experimentally measured values. Using the table [13], the corresponding value of the number can be found, which is an argument of the function ierfc , the value of which allows determining the coefficient of thermal conductivity, using the right side of the equation (15):

$$a = \frac{1}{4 \cdot \tau_2} \left(\frac{x}{B} \right)^2, \quad (16)$$

as $\varphi = \sqrt{a}$.

The coefficient of the mat thermal conductivity can be calculated using the following equation:

$$\lambda = b \cdot \sqrt{a}. \quad (17)$$

Accordingly, the specific heat capacity of the mat made from the reed is found from the ratio:

$$c = \frac{\lambda}{a \cdot \rho}, \quad (18)$$

where is the ρ – density of the reed product, kg/m³.

In any case, a complex determination of the thermophysical characteristics of a reed product based on the solution (6) involves knowledge of the nature of the change in temperature over time at any two points of the testing sample.

These dependencies (16) – (18) are adequate to those obtained for the determination of thermophysical characteristics in [14], and the results of determination of thermophysical characteristics coincide within the margin of error of studies.

Thus, the obtained dependencies allow calculating the thermophysical characteristics of the wood during thermal action.

6. Research results

To establish the thermophysical characteristics of the mat made from reeds, the study of the thermal conductivity under the action of the heating device (Figure 3) was completed. The studies on the maximum temperature ($0.5T$, °C) and the duration of the induction time of temperature transfer through the mat layer made of reeds were performed using the above-mentioned method and equipment, and the respective results are shown in Figure 4.



Figure 3. The process of determining the thermal conductivity of the mat sample made from reeds under the action of a heater.

As Figure 4 shows, the action of the heater led to the intense heat transfer and a slight increase in temperature on the reverse surface of the sample lasting for about 1800 s. As a result of the tests, it was found that the thermal conductivity of this sample is characterized by the reeds itself.

It is established that the mechanism of thermal insulation by the transfer of energy through the material is the braking, caused by air barriers, which makes the influence on this process possible.

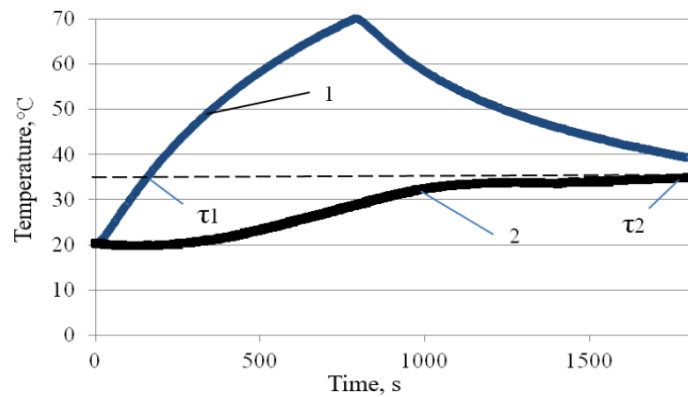


Figure 4. Results of tests of thermal conductivity of the mat made of reeds:

1 – heating curve, 2 – temperature value on the reverse surface of the mat.

The points τ_1 – correspond to the average value of the temperature of the heating curve and τ_2 – correspond to the average value of the temperature on the reverse surface.

The thermophysical characteristics of the reed products were calculated using the above-described method (Table 1) and the results of the measured temperature.

Table 1. Thermophysical characteristics of the reed products

Name of the material	Thickness, mm	Mass, gr	Estimated characteristics of the reed products				
			Density, ρ , kg/m ³	Thermal activity, $W \cdot s^{1/2}/(m^2 \cdot K)$	Temperature conductivity, m ² /s	Thermal conductivity, λ , W/(m·K)	Heat capacity, kJ/(kg·K)
Mat made from reeds 180 × 155 mm	25	96	137.6	200.1	$0.08 \cdot 10^{-6}$	0.056	5.08

Studies have shown that a sample of an insulation product made from reeds reveals thermophysical properties, namely, the coefficient of thermal conductivity (Table 1), which approximates to one of the thermal insulation materials ($\lambda = 0.07 \text{ W} / (\text{m} \cdot \text{K})$) [14-16].

7. Conclusions and prospects for further studies

Thermal conductivity is the process of transferring heat energy from heated parts of a room to fewer warm ones, and energy exchange will occur until the temperature is balanced. The coefficients of thermal conductivity of some building materials depend on many factors: the nature of the material, its structure, the degree of porosity, the nature of the pores, the humidity and the average temperature at which the heat transfer occurs. This corresponds to the data reported in the works [5, 6], whose authors also relate the effectiveness of thermal insulation materials from organic raw materials.

In contrast to the results of the authors' studies [5, 9], the obtained data on the influence of the structure on the heat transfer process and changes in the insulating properties allow us to state the following:

- the main regulator of the process is the density and porosity of the material since the high density and low porosity leads to a rapid equilibration of temperatures, and with increased humidity and wetting of the walls of the building, their open throat factor will be higher;
- a significant influence on the process of thermal conductivity in the application of wood material is in the direction of orientation of the natural material.

The research results of the thermal conductivity process in the material made from the reeds (Figure 1) indicate an ambiguous nature. Such ambiguity cannot be solved within the framework of the present

research, as additional experiments would be required to obtain more reliable data. In particular, this implies the availability of data sufficient for the qualitative completion of the heat transfer process and determination of the starting point of time for the fall of heat resistance. Such determination will allow us to investigate the transformation of the surface of the material produced based on reeds, moving in the direction of high temperature with increasing time of transfer, as well as to identify those variables that significantly affect the beginning of the process transformation.

This work is a continuation of the research presented in [1], that explores the mechanism of transfer and insulation of high temperature by the organic natural material.

This work was prepared as part of the research work "Development of flame retardant materials for natural flammable roof structures (straw and reeds)" of the Ministry of Education and Science of Ukraine.

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