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ТЕПЛОПРОВОДНОСТЬ ДРЕВЕСНЫХ МАТЕРИАЛОВ ЯЧЕИСТОЙ КОНСТРУКЦИИ

А.А. Лукаш, канд. техн. наук, доц.
Н.П. Лукутцова, д-р техн. наук, проф.
Брянский государственный инженерно-технологический университет, просп. Ст. Димитрова, д. 3а, г. Брянск, Россия, 241037; e-mail: mr.luckasch@yandex.ru, natluk58@mail.ru

Разработана физическая модель нагрева пакета слоистого материала ячеистой конструкции из лущеного шпона, предложены зависимости для определения его теплопроводности в условиях нестационарного теплообмена. Установлено, что для пакета из 11 слоев березового шпона толщиной 2 мм коэффициент температуропроводности составляет $1{,}93 \cdot 10^{-6}$ м^2/с. На основе фундаментальной теории теплопроводности древесины получены зависимости для расчета продолжительности склеивания теплоизоляционных материалов ячеистой конструкции. Доказано, что продолжительность склеивания фанерной ячеистой плиты толщиной 22 мм из березового лущеного шпона под давлением составляет 14,5 мин при температуре плит пресса 110 °С. Определены теплотехнические характеристики нового древесного материала ячеистой конструкции: коэффициент теплопроводности ячеистой фанерной плиты плотностью 530 кг/м^3 – 0,081 Вт/(м·K), прочность при статическом изгибе плиты параллельно волокнам наружных слоев – 14 МПа, перпендикулярно волокнам – 10 МПа. Обосновано применение мало используемой древесины мягких лиственных пород с низкими эксплуатационными свойствами в качестве теплоизоляционного материала там, где не требуются высокие прочностные показатели, так как ее коэффициент теплопроводности в 2 раза ниже, чем у аналогичного материала – сплошной фанерной плиты.

Для цитирования: Lukash A.A., Lukutsova N.P. Thermal Conductivity of Wood-Based Cellular Structures // Изв. вузов. Лесн. журн. 2020. № 1. С. 146–153. DOI: 10.37482/0536-1036-2020-1-146-153

Ключевые слова: плита фанерная ячеистая, древесина мягких лиственных пород, теплопроводность, шпон, склеивание, теплообмен.

Поступила 03.06.19 / Received on June 3, 2019

МЕХАНИЧЕСКАЯ ОБРАБОТКА ДРЕВЕСИНЫ И ДРЕВЕСИНОВЕДЕНИЕ

UDC 674.02
DOI: 10.37482/0536-1036-2020-1-146-153

THERMAL CONDUCTIVITY OF WOOD-BASED CELLULAR STRUCTURES

A.A. Lukash, *Candidate of Engineering, Assoc. Prof.*
N.P. Lukutsova, *Doctor of Engineering, Prof.*
Bryansk State Technological University of Engineering, prosp. Stanke Dimitrova, 3A, Bryansk, 241037, Russian Federation; e-mail: mr.luckasch@yandex.ru, natluk58@mail.ru

A physical model is developed for heating a set of laminated cellular structure formed from peeled veneer, dependences for determining its thermal conductivity under conditions of non-stationary heat transfer are proposed. It was found that for a package of 11 layers of birch veneer 2 mm thick, the thermal diffusivity is $1.93 \cdot 10^{-6}$ m^2/s. Based on the fundamental theory of thermal conductivity of the wood substance, dependencies are obtained for calculating the duration of bonding of heat-insulating materials of a cellular structure. It has been established that the duration of gluing of a 22 mm thick plywood mesh slab of peeled birch veneer under pressure exposure is 14.5 minutes at a temperature of press plates 110 °C. The thermotechnical characteristics of the new wood-based cellular structure material were determined: the thermal conductivity coefficient of a cellular plywood board with a density of 530 kg/m^3 was 0.081 W/(m·K), the strength under static bending of the board parallel to the fibers of the outer layers was 14 MPa, and perpendicular to the fibers was 10 MPa. The use of underutilized soft broadleaved species with low operational properties as a heat-insulating material, where high strength indicators are not required, is justified, since its thermal conductivity is two times lower than that of a similar material – solid plywood board.
For citation: Lukash A.A., Lukutsova N.P. Thermal Conductivity of Wood-Based Cellular Structures**.** *Lesnoy Zhurnal* [Russian Forestry Journal], 2020, no. 1, pp. 146–153. DOI: 10.37482/0536-1036-2020-1-146-153

Keywords: plywood cellular board, hardwood, thermal conductivity, veneer, gluing, heat exchange.

Introduction

Housing is an actively developing industry. Wood has certain strength characteristics and good heat insulation indicators. Low-rise wooden house construction provides the most favorable and comfortable living conditions [3, 5]. The creation of effective heat insulation materials for wooden house construction is in accordance with Federal Law No. 261-FL "On Energy Saving and on Improving Energy Efficiency and on Amending Certain Legislative Acts of the Russian Federation." Besides that, the use of broadleaved species corresponds to the Strategy for the Development of the Forest Complex of the Russian Federation for the period up to 2020 [11]. Therefore, the topic of research aimed at improving technologies for the creation of effective thermal insulation materials from underutilized wood species is relevant and significant.

The aim of the research is to determine the thermal conductivity of new wood materials of cellular structure made of peeled veneer. Scientific novelty is dependencies for determination of thermal conductivity of cellular construction materials.

The possibility of creating new thermal insulation materials from hardwood with thermal insulation properties superior to those of existing similar products is theoretically and experimentally justified. The practical significance of the research lies in the development of resource-saving and energy-saving technologies for obtaining new heat-insulating materials with improved thermal characteristics from wood with low operational properties.

The material studied was hardwood deciduous species. The provisions of the theory of thermal conductivity of wood were applied.

Results of studies

Good performance properties of coniferous wood [17] provide increased demand, as a result of which there is a shortage in the Central European part of the country. The volume of use of deciduous species is only 15 % of the annual estimated cutting area. Therefore, the issues of processing of low-demand deciduous species are relevant for the industry of our country. In addition, in industrialized countries there is an increased interest in the practical use of hardwood due to its rapid growth [14, 19].

Wood materials from deciduous species most rationally to apply for thermal insulation in construction where high strength indicators are not required. But new building materials will be in demand if they have higher performance than existing similar products.

As is known, the main difference between the microstructure of hardwoods and conifers is the presence of vessels [1, 12]. Highly developed vessels displace adjacent cells, so that hardwood does not have the correct structure that is characteristic of softwood. Presence of vessels provides good impregnation properties [13, 15, 16, 18] and possibility to apply deforming treatment without formation of cracks [20].

The presence of closed air cavities in the vessels provides soft hardwood with low thermal conductivity. Therefore, in order to reduce thermal conductivity in new wood thermal insulation materials, it is necessary to create a cellular structure with closed air layers.

A new thermal insulation material is a plywood cellular plate made of veneer (Fig. 1) [4, 8].

Fig. 1. Plywood cellular plate from an interline interval

Novelty of method and device for its manufacture are confirmed by russian patents [6, 7]. The inner layers of the plywood honeycomb plate consist of strips of veneer laid with a gap so that each subsequent strip overlaps the gap between the previous layer. The presence of gaps between the veneer strips of the inner layers increases the thermal insulation properties and saves raw material. A hot press is used for gluing.

Plywood cellular plate is a new under-investigated material. There are no gluing modes and thermal characteristics are unknown. Therefore, dependencies are proposed to calculate the duration of gluing.

It is known that the duration of gluing of wood laminates of solid construction depends on the duration of heating of the glued bag to a temperature of 100 °C or higher. In its turn, duration of heating is determined by coefficient of thermal conductivity of glued material. The structure of existing wood laminates is uniform throughout the section. When such materials are heated, heat transfer occurs at a constant rate throughout the section, making the heat exchange stationary.

The processes of gluing uniform materials have been studied and described in sufficient detail in the scientific and reference literature, and the calculation of the gluing duration itself is not difficult. But in a plywood cellular plate containing internal air layers, the heat transfer process inside the stack is not constant due to the different heat conductivity coefficients of the wood and air. Therefore, the heat conductivity coefficient of materials with a non-uniform internal structure under non-stationary heat exchange conditions was calculated. The physical heating model of the stud pack is shown in Fig. 2.

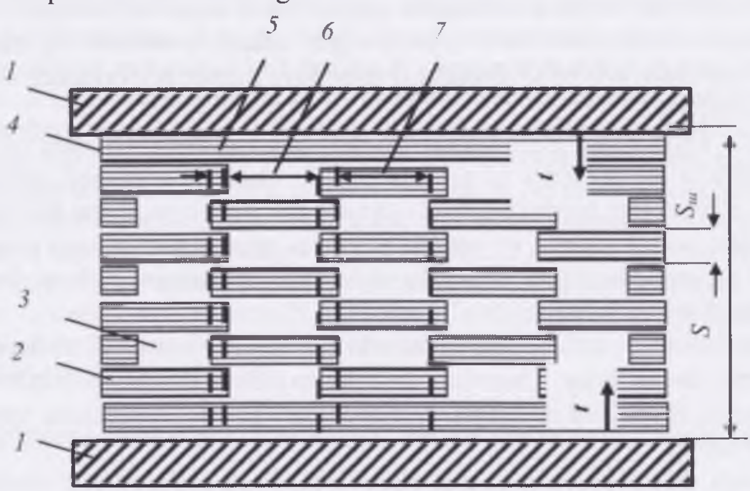

Fig. 2. Physical model of pack heating: *1* – press heating plates; *2* – spline strips; *3* – full-length sheet of the tongue; *4* – air layers; *5* – area without air layers; *6* – area with maximum number of air layers; *7* – section with air layers (*S* – thickness of package; $S_ш$ – thickness of veneer)

The cross section of the stud pack can be divided into solid sections without air layers *5* and sections with air layers *6* and *7* (Fig. 2). The duration of heating of the inner adhesive layer most distant from the press plate to 100 °C on each of the sections is calculated. First, we will calculate the area *7* containing the largest number of air layers. In this area, the package consists of *n* layers and *k* air layers and *m* wood layers. Number of layers *n*, pcs, will be determined

$$n = k + m = (m - 1) + m = 2m - 1. \quad (1)$$

Heating of a package of an interline interval is interfered by the thermal resistance of R, (м^2·K)/W which is determined by a formula

$$R = \frac{s}{\lambda}, \quad (2)$$

where S – thickness of a package, m; λ – coefficient of heat conductivity of a package, W/(m·K).

Total thermal resistance of the stud stack, R, (m^2·K)/W, is defined as the sum of the thermal resistances of the air layers and wood layers [9, 10]

$$R = k\,R_в + m\,R_д, \quad (3)$$

where $R_в$ – thermal resistance of air, (м^2·K)/W; $R_д$ – thermal wood resistance, (m^2·K)/W.

From here

$$\frac{s}{\lambda} = k\,\frac{\delta_в}{\lambda_в} + m\,\frac{\delta_д}{\lambda_д}, \quad (4)$$

where $\delta_в$ и $\delta_д$ – Respectively thickness of air layer and wood layer, m.

Using the same-thickness stud $S_ш$

$$\delta_в = \delta_д = S_ш. \quad (5)$$

Considering (1–4)

$$\frac{(2m-1)S_ш}{\lambda} = \frac{(m-1)S_ш}{\lambda_в} + \frac{mS_ш}{\lambda_д}, \quad (6)$$

or

$$\frac{(2m-1)}{\lambda} = \frac{(m-1)}{\lambda_в} + \frac{m}{\lambda_д}. \quad (7)$$

Considering that the thermal conductivity coefficient λ numerically equal to product of thermal conductivity coefficient (α), density (ρ) и specific heat capacity (c) we obtain

$$\frac{2m-1}{\alpha_п \rho_п c_п} = \frac{m-1}{\alpha_в \rho_в c_в} + \frac{m}{\alpha_д \rho_д c_д} \quad (8)$$

where $\alpha_п$, $\alpha_в$ and $\alpha_д$ – temperature conductivity factors of the stack, air and wood, respectively, m^2/s; $\rho_п$, $\rho_в$ and $\rho_д$ – accordingly, the density of the stair pack, air and wood, kg/m^3; $c_п$, $c_в$ and $c_д$ – respectively specific heat of a package of an interline interval, air and wood, kJ/(kg·K).

Package density $\rho_п$, the kg/m^3 will make

$$\rho_п = [(m-1)\,\rho_в + m\,\rho_д] / (2m-1). \quad (9)$$

Similarly, we find the specific heat capacity of the stair pack

$$c_п = [(m-1)\,c_в + m\,c_д] / (2m-1). \quad (10)$$

From there

$$\alpha_п = (2m-1) / \{[(m-1) / (\alpha_в\,\rho_в\,c_в) + m / (\alpha_д\,\rho_д\,c_д)]\,\rho_п\,c_в\}. \quad (11)$$

The temperature of the stud pack varies from 20 °C to 100 °C during heating. The values of the specific heat capacity of the stair pack and the coefficient of thermal conductivity are taken as arithmetic mean for simplification of calculations.

The value of specific heat capacity of wood depending on its humidity and temperature is selected according to [2, p. 145].

The specific heat of air will be 1.005 kJ/(kg·K), and at 100 °C 1.009 kJ/(kg·K). For calculations we accept $\alpha_в = 1.007$ kJ/(kg·K).

The coefficient of thermal diffusivity of air $\alpha_в$ at a temperature of 20 °C makes $20.8 \cdot 10^{-6}$ m²/s. The thermal diffusivity coefficient at a temperature of 100 °C makes $33.1 \cdot 10^{-6}$ m²/s. For calculations we accept as averaged $\alpha_в = 26.95 \cdot 10^{-6}$ m²/s. Values of wood thermal conductivity coefficient are selected depending on wood temperature and humidity [2].

When moisture content is 15 %, the thermal conductivity factor of the wood $\alpha_д$ at temperature 20 °C is $1.51 \cdot 10^{-7}$ m²/s. n case of 15 % moisture, the coefficient of wood thermal conductivity at temperature of 100 °C is when moisture content is 15 %, the thermal conductivity factor of the wood $\alpha_д$ at temperature 100 °C makes $1.61 \cdot 10^{-7}$ m²/s. For calculations we accept $\alpha_в = 1.56 \cdot 10^{-7}$ m²/s.

The calculation of the heating time of the stack is shown in Table.

Parameters of the package to be glued

Indicators	Wood	Air	Package
Density, kg/m³	640	1,225	350
Coefficient of thermal conductivity, m²/s	$1.56 \cdot 10^{-7}$	$2.7 \cdot 10^{-5}$	$1.93 \cdot 10^{-6}$
Specific heat, kJ/(kg·K)	2.25	1.007	1.68

For a 22 mm thick stair pack in which there are 5 layers of wood and 2 layers of air in the 6 area (Fig. 5), with the thickness of each layer 2 mm, the density of the pack $\rho_п$, kg/m³ will make

$$\rho_п = [5 \cdot 1.225 + 6 \cdot 640] / 11 = 350.$$

Specific heat capacity of the stair pack $c_п$, kJ/(kg·K) will make

$$c_п = [5 \cdot 1.007 + 6 \cdot 2.25] / 11 = 1.68.$$

Thus, when gluing the plywood cellular plate, the coefficient of thermal conductivity of the pack of 11 layers of birch stew with a thickness of 0.002 m will be $\alpha_п = 1.93 \cdot 10^{-6}$ m²/s. We will calculate the gluing time of this packet. The most distant adhesive layer from the press plate is at a distance equal to half the thickness of the bag (0.011 m). The design ratio *X/S* will be

$$X/S = 0.011/0.022 = 0.5.$$

Reference temperature of a t_n package is 20 °C, the set temperature of heating of the press of a glue layer of t_3, most remote from a plate, will be 100 °C, temperature of plates of a press of t_{pl} – 110 °C. Dimensionless temperature θ for the specified temperatures will be:

$$\theta = \frac{110 - 100}{110 - 20} = 0.11\,.$$

Fourier's criterion is chosen on the graphic dependences given [2] depending on value of dimensionless temperature θ and the relation of *X/S*. For Для θ = 0.11 and *X/S* = 0.5 find Fourier criterion value

$$F_0 = 1.05.$$

Considering that duration of heating up to 100 °C the most distant from press plates adhesive layer t_1, min. is determined by formula

$$\tau_1 = \frac{S^2 F_0}{4\,\alpha_п}, \qquad (12)$$

where S – thickness of packet to be glued, m; $\alpha_п$ – termal conductivity coefficient of a package, m^2/s; F_0 – fourier's criterion.

Duration of heating of the press of a glue layer, most remote from plates, to 100 °C, τ_1, mines, will be minutes:

$$\tau_1 = \frac{0.022^2\ 1.05}{4 \cdot 0.000000156} = 814.4c = 13.6\,.$$

Taking into account gelation time at temperature 100 °C, τ_2, minutes The total gluing time will be:

$$\tau_п = \tau_1 + \tau_2 = 13.6 + 0.9 = 14.5 \text{ minutes.}$$

The validity of the proposed dependencies has been confirmed experimentally. A 22 mm thick plywood mesh plate was glued from the birch peeled veneer at press plate temperature 110 °C and pressure exposure time 14.5 minutes.

Thermal characteristics of plywood cellular plate are determined. The value of the cellular plywood plate with density of 530 kg/m^3 thermal conductivity coefficient obtained by pre-6 dependencies was 0.082 W/(m·K). The experimental value of the thermal conductivity coefficient determined by the special device ITP-MG4 "100" according to GOST 7076–99 was 0.081 W/(m·K).

Good coincidence of theoretical and experimental data confirms the validity of the calculations. Thermal conductivity coefficient of cellular plywood plate with density is twice lower than that of conventional plywood plate. Strength at static bending of plywood cellular plate with thickness of 0.015 m parallel to fibers of external layers – 14 MPa, perpendicular to fibers – 10 MPa.

Conclusion

1. A physical model is developed for heating a package of layered material of a cellular structure from peeled veneer, and dependences are proposed for determining its thermal conductivity under conditions of unsteady heat transfer. It was found that for a package of 11 layers of birch veneer 2 mm thick, the thermal diffusivity is $1.93 \cdot 10^{-6}$ m^2/s.

2. Based on the fundamental theory of wood thermal conductivity, dependencies are obtained for calculating the duration of bonding of heat-insulating materials of a cellular structure. It has been established that the duration of gluing of a 22 mm thick plywood mesh slab of peeled birch veneer under pressure exposure is 14.5 minutes at a temperature of press plates 110 °C.

3. The thermotechnical characteristics of the new wood-based material with a cellular structure were determined: the thermal conductivity coefficient of a cellular plywood board with a density of 530 kg/m^3 was 0.081 W/(m·K), the strength under static bending of the board parallel to the fibers of the outer layers was 14 MPa, and perpendicular to the fibers was 10 MPa.

4. The use of poorly used deciduous wood with low operational properties as a heat-insulating material, where high strength indicators are not required, is

justified, since its thermal conductivity is two times lower than that of a similar material – solid plywood board.

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