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# DETERMINING THERMAL AND PHYSICAL CHARACTERISTICS OF WOOD POLYMER MATERIAL FOR PIPELINE THERMAL INSULATION

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***One of the methods for ensuring the efficiency of pipelines for transporting heat-carriers during operation is their thermal insulation, which inhibits heat transfer processes and does not affect environmental indicators. Therefore, the object of research was wood, a polymer material made by polymerization of wood sawdust and dry mixtures of synthetic resins for thermal insulation of pipelines. It has been proven that in the process of thermal action on the heat insulating layer of wood polymer material, the process of heat inhibition involves the formation of pores. This is due to the fact that the thermal conductivity of the material depends on the volumetric mass, the decrease of which for a wood polymer product leads to a decrease in thermal conductivity. In this regard, the simulation of the process of heat transfer through a cylindrical heat-insulating layer made of wood of polymer material was carried out and the dependences derived, which allow obtaining a change in the dynamics of heat transfer and determining thermophysical properties. According to the experimental data and the established dependences, it was found that the thermal conductivity of the wood of the polymer material was within $2.4 \div 2.9 \cdot 10^{-8}$ m²/s, the thermal conductivity of the sample did not exceed 0.030 W/(m·K). In addition, the heat capacity of the product corresponds to a value of more than 1034÷1145 kJ/(kg·K) depending on the thickness, which accordingly categorizes it as a heat-insulating material. At the same time, data on thermal insulation properties for polyurethane foam show that when it is used with a density of 100 kg/m³, the thermal conductivity is 0.029 W/(m·K), which is approximately the same as the value of the proposed wood polymer material. The practical value is the fact that the results of determining the heat-insulating properties of a wood polymer material make it possible to establish the scope and conditions of its application***

***Keywords:** wood sawdust, binder resins, wood polymer material, thermal insulation of the pipeline, thermal conductivity*

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## 1. Introduction

Thermal insulation plays an important role in the development of construction as it saves energy resources, stabilizes heat-generating processes and equipment, gives buildings an aesthetic appearance and ensures durability. It is important to use insulation to preserve negative temperatures, particularly in agriculture to preserve products.

Solving this task requires the development of new types of thermal insulation products, the materials of which can be waste from the woodworking industry.

Thus, the basic product for the manufacture of thermal insulation from wood is sawdust, which has a number of positive properties, such as low price, durability, environmental friendliness. In addition, chopped wood can absorb condensation if the air becomes too humid, and evaporate it in the opposite situation. But it also has negative properties, in particular, a tendency to rot, which can occur due to moisture or ineffective ventilation, etc. The use of binders based on synthetic resins in the formation of heat-insulating products from wood sawdust increases the environmental safety and weather resistance of the products since such resins are characterized by resistance to water and temperature changes. It also reduces the formation of microorganisms in the structure of the product because the material that insulates the building becomes stronger and harder and does not sag over time. All of this leads to a reduction in the complexity of installing thermal insulation for the building and the ability to heat-insulate heat-generating equipment and heat-carrier pipelines, the cost of building materials, and a reduction in the share of energy carriers for heating.

Thus, the main technical characteristic of the resulting thermal insulation materials is thermal conductivity, that is, the ability of the material to transfer heat, which depends on the density of the material, the type of binder, the location of the cells, etc. Therefore, there is a need to determine the thermophysical properties of wood sawdust products and binder dry mixtures of resins for thermal insulation of pipelines, which predetermines the need for research into this area.

## 2. Literature review and problem statement

Paper [1] notes that centralized heating systems offer solutions for solving growing energy problems in densely populated cities. Energy costs increase depending on the increase in heat losses in the DHS distribution network. Heat losses from the grid make up 5–20 % of the transmitted energy, and these losses exceed other losses in the heating system. In the study, heat loss from pipes such as supply-return pipes, hot water pipes, and circulation pipes to heat ducts is investigated on the basis of energy, exergy, economics, and ecology. Optimum insulation thickness, energy savings, $CO_2$ reductions, first investment costs and payback periods for pipes in district heating networks of all generations are investigated using the Life Cycle Cost Analysis (LCCA) method for fuel types such as natural gas, fuel oil, and coal. The optimal insulation thickness is calculated for different nominal pipe sizes and different insulation materials, such as glass wool and rock wool, for different climate zones. According to the research results, the pipe heat loss in the 4th generation DHS network is reduced between 38.19 % and 33.33 % from the warmest climate zone to the coldest climate zone according to the 3$^{rd}$ generation. Energy savings, $CO^2$ emissions reduction, payback periods and optimal values of the insulation thickness of the supply and return pipe in the network vary between USD 7.80–98.86/m, 39.61–322.32 kg $CO_2$/year, 0.028–0.38 years, and 0.025–0.0105 m depending on different types of fuel, insulating materials, nominal pipe sizes, climatic zones and all types of generation. However, it is not said how these materials affect the environment.

Work [2] examines the oscillations of three-layer cylindrical pipes and reports the equations of motion of a three-layer cylindrical shell with a lightweight filler, reinforced with stiffeners, under a non-stationary load. Numerical results of vibrations of a three-layer elastic structure were obtained using the finite element method. The influence of the physical and mechanical parameters of the shell layers on its stress-strain state under axisymmetric internal impulse loading was studied. However, it is not said how this affects operation.

In study [3] it is noted that heat loss should be minimized at relatively low investment costs in order to economically find the most suitable insulation thickness. Numerous studies have focused on analytical (1D model) calculations and numerical simulations. However, there is a research gap related to laboratory instruments that allow measurement of operating parameters (fluid flow, fluid temperature in the supply pipe and return pipe). The cited article presents the analysis of heat losses from pre-insulated pipes and double pipes in the heat supply network. The study compares heat loss in the ground calculated by an analytical solution (1D model) with measurements in a special experimental setup. Calculations were performed for several options of heat network pipes: double pipes: DN40, DN50, DN65, and their analogs in a single parallel pre-insulated system. The insulation thickness used in all cases was 30.85 mm for DN40 and 32.00 mm for DN50 and DN65. The insulation was made of rigid polyurethane foam that meets the requirements of the PN-EN 253 standard. During the study, the thermal conductivity of the insulating material was checked. The thermal conductivity results were used in calculations. The results of laboratory instruments and analytical models were compared, showing good agreement – with a low level of error in the range of approximately 8 %, depending on the type of centralized heating pipe. The validated mathematical model of the heat network was then used to calculate heat losses in the heat network connecting the underground storage tank to the ground source heat pump. However, there is no definition of optimal solutions for its spatial location.

In [4], silicate airgel is presented as the lightest solid material, known as a new type of super heat-insulating material with the advantages of low thermal conductivity, high porosity, and high specific surface area. However, silica airgel suffers from poor mechanical characteristics and high cost, which significantly hinders its widespread use in thermal insulation. In the work, synthesis technologies and methods for improving the mechanical properties of silica airgel were considered, and their influence on airgel characteristics is analyzed from the point of view of control of the preparation process, optimization of aging conditions, heat treatment, fiber and polymer composite. The focus is on the application of silica airgel for thermal insulation in aerospace, military industry, industrial pipelines, building insulation, new energy vehicles, and other fields in recent years, and the technical problems are analyzed. It is noted that in the future it is necessary to further expand the operating temperature range, to consider the methods of co-precursors and chemical cross-linking to improve the thermal insulation characteristics at high temperature, and also to solve the problems of "powder loss" of airgel-gel fiber composite and uneven dispersion of micron powder, especially the rapid development of new fields applications such as new energy vehicles. However, silica airgel synthesis technologies require further development and optimization for new application requirements.

Work [5] argues that the insulating material cannot be chosen in industry only on the basis of its cost or thickness. A balance must be maintained between cost and safety, which are considered top priorities in the industry over time. This document discusses a much simpler method of comparing the effects of different insulation materials for a given system and determining the best material and thickness. Heat losses at different process temperatures and different insulation materials for different pipe diameters were obtained using simulations in ANSYS. Theoretical calculations were then used to determine the optimal thickness of insulation in relation to the cost and heat loss of the system, as well as, if necessary, the temperature of the external surface of the system. This is important because too much isolation can lead to increased costs while too little leads to reduced security. For the study, 1-, 2-, and 4-inch stainless steel pipes were considered, along with EPS polystyrene, XPS polyurethane, and fiberglass insulation materials.

The novelty of article [6] is that a new strategy was proposed: the use of district heating (DH) pipe liners that are cured in place (CIPP). This strategy can implement maintenance of pipes without repairs and large excavations. To support this strategy, a new CIPP liner has been developed with an improved isolation function. The resulting CIPP liner demonstrated several advantages, including low thermal conductivity, high mechanical properties, low water absorption, and high thermal stability. The effect of using CIPP liners was influenced by liner parameters and operating conditions. According to the set of parameters, the liner reduced the heat loss of the old pipe by 55.4 %. But this does not remove the question of suppressing the destruction of pipeline elements.

Building on these studies [7], aerogels have great research significance in the field of engineering insulation, pipeline transport, and packaging insulation as advanced materials for thermoregulation. The composite interaction of the two-phase interface and the construction of the porous structure have an important effect on the thermal properties. Here, a novel HANRs/SAB composite airgel was fabricated using sodium alginate (SA) with hydroxyapatite nanorods (HANRs) combined with boric acid cross-linking and freeze-drying. In the as-prepared sample, calcium ions in HANR and SA formed the first layer of binding force, and the chemical crosslinking of sodium alginate with boric acid formed a second layer of strong binding force, which effectively supported the airgel skeleton and enhanced the overall binding force. mechanical properties. The modulus and ultimate compressive strength of the obtained HANRs/SAB airgel were 2.39 and 0.75 MPa, respectively, while the bulk density was $0.038–0.068\ g\cdot cm^{-3}$. Based on the outstanding physical structure, the prepared HANRs/SAB airgel exhibited good thermal insulation (~35.15 mW/(m·K)) and outstanding flame-retardant performance. The flame-retardant boric acid and high thermal stability of HANR can effectively prevent heat transfer and organic combustion, resulting in extremely low flue gas emissions ($11.3\ m^2/m^2$). Thus, the low-cost biopolymer composite airgel based on the crosslinking strategy has broad application prospects in the field of thermal insulation and fire resistance. However, the values of these parameters do not cover a wide range of applications.

Work [8] investigates various approaches to optimization for determining the optimal thickness of insulating layers in civil and industrial pipeline systems. The process is carried out by introducing the concept of embodied energy and controlled carbon emissions, together with the economic evaluation of investments related to insulation. Several technical and economic characteristics are considered, for example, pipe size, insulating materials, heat-carrier, operating temperature, climatic conditions, etc. The results show that pipeline geometry, operating conditions and system heating have a strong influence on the optimal insulation thickness while climatic conditions have little effect, especially for operating fluid temperatures above 45 °C. However, the country of origin of the insulation strongly affects the achievable net carbon savings due to the different embodied emissions associated with the local energy consumption used.

Study [9] aimed to determine the influence of the optimal thickness of pipe insulation on energy saving and air pollution in greenhouse conditions. In this regard, an optimization model based on life cycle cost (LCC) analysis was carried out using the P1–P2 method. Three fuels, coal, natural gas, and fuel oil were tested with nominal pipe sizes from 25 to 65 mm, and hot water was used in the system. The results showed that the highest insulation thickness (0.807 m), the highest energy savings (USD 62.351/m), and the lowest payback period (0.502 years) were achieved with the 65 mm fuel oil pipe size. In general, insulation minimizes heat loss through heat pipes, resulting in economic and environmental benefits. Thus, for the use of fuel oil, $CO_2$ emissions ranged from 2.762 to 3.798 kg/m, and $SO_2$ from 0.014 to 0.020 kg/m for pipes with a thickness of 25 and 65 mm, respectively. However, the results highlighted the low participation of fuel oil in the environmental impact.

In work [10], it is proposed to use heat-insulating materials that are usually used under conditions of low temperatures, such as pipelines for the transportation of liquefied natural gas, they can become brittle and therefore susceptible to shock damage. The novel feather fiber biomaterials developed in the work have extremely low thermal conductivity but retain high impact resistance at low temperatures. The reported experiments demonstrate improved impact resistance of feather fiber biomaterials compared to foamed nitrile rubber. The microstructural characteristics of feather-fibrous biomaterials, which allow them to be used as impact-resistant thermal insulation at low temperatures, are discussed.

Paper [11] states that corn straw was converted into straw powder (SP) by physical processing in order to obtain solid polyurethane composite foams by a one-step method. The resulting foams were evaluated for mechanical properties, thermal properties, and cellular structure. It was found that the compressive strength of the composite foams decreased dramatically compared to the pure foam, and the powder size had no obvious effect on the compressive strength in the growth direction. The flexural strength of rigid polyurethane composite foams with corn straw decreased from 0.34 MPa (pure foams) to 0.22 MPa and 0.26 MPa, a decrease of 35.3 % and 23.5 %, respectively. The flexural strength of the non-growing rigid polyurethane composite foam decreased slightly with increasing powder size. SEM indicates that the porous foam was denser due to the addition of SP. However, in all composite foams, non-uniform distribution and more broken cells were observed. Compared to pure foams, the thermal properties of rigid polyurethane composite foams with corn straw did not change, however, when SP was added to the matrix, more heat flow was released compared to pure foams. All the results show that polyol can be replaced by corn straw in the polyurethane industry, realizing an environmentally friendly alternative to polyester polyol with corn straw in the manufacture of rigid polyurethane composites. Rigid polyurethane foams have a good thermal insulation effect and are mainly used in the field of thermal insulation, such as insulation material for refrigerators, insulation material for chemical transport pipelines, thermal insulation layer on the surface of building walls, etc.

The aim of study [12] was to determine the heat transfer in natural insulation made of rice husk ash and sheep wool (SWRHA), rice husk ash with sisal fibers (SFRHA), rice husk ash with banana fibers (BFRHA), and air gap insulation. The steel pipes had an internal diameter of 63 mm and a length of 1 meter. The length (1.1 m) and the diameter of the pipe insulation were the same (172 mm). On the other hand, the thicknesses of BFRHA, SFRHA, SWRHA, and asbestos insulation pipes were 80 mm and 106 mm, respectively. The maximum thermal conductivities of sisal fiber, sheep wool, banana fiber, and rice husk ash were (0.045, 0.044, 0.094, and 0.4) W/m·K, respectively. The maximum and minimum heat losses of BFRHA, SFRHA, SWRHA with air gap and asbestos insulation were (225.132, 223.38, 222.33 and 1328.271) kWh/year, and (41.70, 52.56, 19.71, and 46,428) kWh/year, respectively. For a unit length of pipe at 90 °C, the maximum energy savings of BFRHA, SFRHA, SWRHA with air gap and asbestos insulation were (244.708, 242.804, 241.602, and 1443.772) kWh/year, respectively. Therefore, as the result showed, the performance of BFRHA, SFRHA, and SWRHA with air gap is better than that of asbestos insulation. The time of operation of these products is not mentioned.

In article [13], the temperature field of the construction of the insulation of the lower wall of the tank was simulated and compared with experimental data to check the accuracy of the model. Based on the original scheme, the load on the structure was reduced due to the introduction of heat pipes. When 10 heat pipes were installed, the thickness of the carbon steel layer in the thermal insulation structure could be reduced from 10 cm to 3 cm or less, and the breakage of some heat pipes would not cause the local temperature of the boundary wall material to exceed. But to achieve prediction accuracy, a more appropriate model should be built.

In [14] it is stated that in order to evaluate the durability of the 4GDH piping material, we analyzed the behavior of the working steel pipe, the insulating foam, and their adhesive interaction using an innovative analytical and experimental procedure. This document describes the effect of traditional and future operating load conditions on the performance of pre-insulated butted single-pipe systems, which represent the majority of current operating central heating piping. A steel pipe fatigue analysis has shown that the life of 4GDH pipelines is expected to increase due to the lower operating temperature and low impact of network thermal load instability compared to conventional DH. Accelerated aging tests on DN 50/160 pipes demonstrated that the combined effect of cyclic mechanical loading and thermal aging accelerates the rate of chemical degradation of polyurethane foam, resulting in faster deterioration of mechanical adhesion strength. Shear strength tests of naturally aged CT pipes showed that, in addition to the initial characteristics of the pipe system and the aging period, the residual shear strength of polyurethane foam (PUR) depends on the temperature history, decreasing with the level of operating temperature and the amount of fluctuation.

Thus, it was established from the literature that the transportation of heat-carriers through domestic pipelines requires the use of environmentally safe heat-insulating materials. These could include products, in particular, from wood sawdust and dry mixtures of synthetic resins, which requires the determination of thermophysical characteristics, the values of which are necessary for design and manufacture. All this gives grounds for conducting a study aimed at determining the parameters that ensure the use of such a heat-insulating product.

## 3. The aim and objectives of the study

The purpose of this work is to establish the thermophysical characteristics of a heat-insulating product made of wood sawdust and dry mixtures of synthetic resins for heat-insulating pipelines. This will make it possible to expand the scope of use of wood to save energy for transportation and heating of buildings.

To achieve the goal, it was necessary to solve the following tasks:

– to model the parameters of the heat exchange process for a cylindrical wood polymer material;

– to establish the features of temperature inhibition through the heat-insulating layer of wood polymer material under thermal influence.

## 4. The study materials and methods

### 4. 1. The object and hypothesis of the study

The object of our study is a heat-insulating wood-composite layer made of wood sawdust and dry mixtures of synthetic resins. The subject of the study is the thermophysical properties of a wood composite layer made of wood sawdust and dry mixtures of synthetic resins under the conditions of thermal insulation.

The hypothesis of the study assumes that by polymerization of dry mixtures of synthetic resins with wood sawdust, it is possible to purposefully adjust the structure and technological properties of wood composite products for thermal insulation of pipelines.

In the course of the research, the following assumptions and simplifications were adopted, which relate to the peculiarities of the flow of heat exchange and other processes at the modeling object:

– which determine the impact of changes in external conditions on the object of research and the lack of interrelationships between process implementations, namely: the flow of heat exchange processes in wood polymer material are the same, temperature, humidity, and pressure are not variable;

– a sample of wood polymer material is homogeneous.

### 4. 2. Investigated materials used in the experiment

To determine the thermophysical characteristics of wood polymer material from wood sawdust and dry mixtures of synthetic resins (polyester), samples were made by mixing sawdust and dry mixtures of polyester resin (Etika polyester powder paint, produced in Turkey) in a ratio of 1:2 and applied to the wood according to [15]. From the resulting mixture, a semi-cylinder with the following dimensions was formed: outer diameter – 40 mm, inner diameter – 24 mm, and length 120 mm, and thermal sintering was carried out at a temperature of 200 °C for 20 min (Fig. 1)

Fig. 1. Samples of products for research

From the obtained samples, a cylinder was created from wood polymer material, on which the thermophysical characteristics were determined.

**4. 3. Procedure for determining the indicators of sample properties**

According to research data, it has been established that during the selection of heat-insulating materials for construction, recommendations from [16] are taken into account, in which normative values of density, thermal conductivity in the dry state, moisture content of the material under conditions A and B, as well as thermal conductivity under these conditions for construction products are given.

Determination of thermophysical indicators of construction products can be carried out according to [17]. The essence of the thermal insulation test method is that the material being tested is subjected to thermal effects that simulate the conditions of use of the material in the enclosing structures, which are panels, and determine the changes in the thermophysical characteristics of the material and should not be used for cylindrical products.

Therefore, in order to obtain values of the thermal conductivity of plant raw materials, special equipment was designed and manufactured, and a cylindrical electric heater simulating a low-calorie heat source was used (Fig. 2).

The heater was made as follows: a nichrome wire with a resistance of 62 ohms and a voltage of 20 V was wound on an electrically insulating hollow cylinder with an outer diameter of 22 mm, an inner diameter of 18 mm, and a length of 90 mm. The heater was placed in a cylindrical sample of the wood polymer material and heat insulated (Fig. 3).

Determining the thermal insulation properties of the wood polymer material for pipelines was carried out by evaluating the thermal conductivity characteristics under thermal action in controlled laboratory conditions. A thermocouple was installed between the studied sample of the wood polymer material, and the heater to control the temperature of the heater, and a thermocouple was placed on the opposite wall of the sample to determine the transfer temperature through the sample [18]. Electrical heating was turned on, the temperature of the heater and the back surface of the sample was measured. When the heater temperature reached 90 °C, the heater was turned off, and the temperature on the back surface of the sample was continued to be measured up to a value of $0.5T_{max}$.

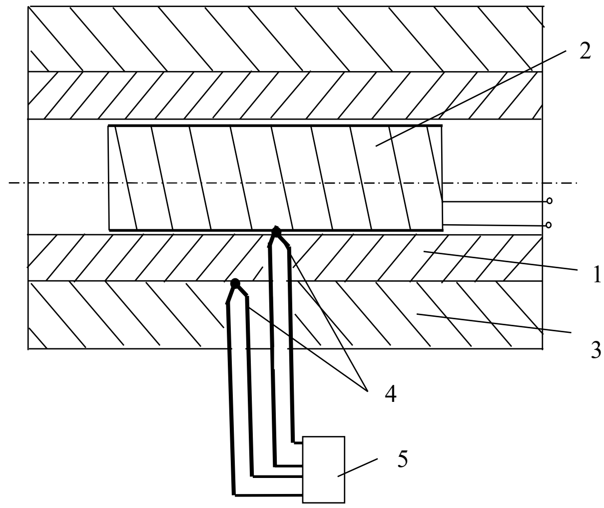
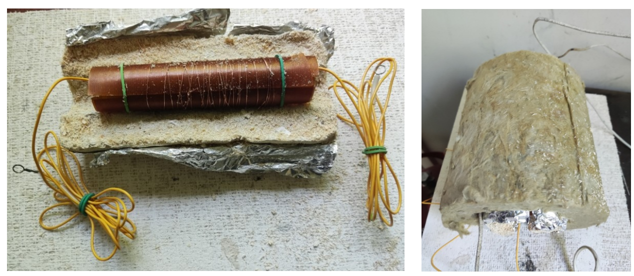



Fig. 2. Device for researching the thermal conductivity of wood polymer material: 1 – wood polymer material; 2 – cylindrical heater; 3 – thermal insulation; 4 – thermocouples; 5 – temperature recording device



*a* *b*

Fig. 3. Device assembly: *a* – cylindrical heater; *b* – heat insulator

Based on the measured values, the thermal insulation properties of the wood polymer material were determined.

## 5. Results of determining the thermophysical characteristics of wood polymer material under thermal influence

**5. 1. Modeling parameters of the heat exchange process of wood polymer material when used for heat insulation of pipelines**

In order to establish the thermophysical characteristics of a wood polymer material, a method for solving the problem of thermal conductivity for a hollow cylinder is proposed [19]. A semi-confined cylindrical body at temperature $T_0$ is given. The inner surface is heated by a constant heat flux $Q$=const. The temperature changes in one direction (Fig. 4). Find the temperature distribution along this direction on the back surface from the heater at any moment of time under the condition of $0.5T_{max}$.

Three areas were considered (Fig. 4):

– 1 – heater medium, $r<0$, m;

– 2 – zone of wood polymer material, $r<R$, m;

– 3 – thermal insulation of the sample, m.

The differential equation describing this process takes the form [20]:

$$\frac{\partial T(r,\tau)}{\partial \tau}=a\left(\frac{\partial^2 T(r,\tau)}{\partial^2 r}+\frac{1}{r}\cdot\frac{\partial T(r,\tau)}{\partial r}\right),\ (\tau>0;\ 0<x<\infty),\quad (1)$$

$$T(r,0)=T_0,\quad (2)$$

$$-\frac{\partial T(R,\tau)}{\partial r}+\frac{q_c}{\lambda}=0,\quad (3)$$

$$T(0,\tau)=0,\quad (4)$$

$$\frac{\partial T(0,\tau)}{\partial r}=0,\quad (5)$$

where $T_0$ – the initial temperature of the sample, °C;

$T(r, \tau)$ – temperature field of the sample at the point with coordinates $r$ at the moment of time $\tau$, °C;

$a$ – thermal conductivity coefficients of the sample, $m^2/s$;

$\tau$ – time the wood sample stays in the high-temperature environment, s;

$q_c$ – temperature flow, $W/m^2$;

$\lambda$ – thermal conductivity coefficients of the sample, W/(m·°C).

The solution to equation (1) with initial and boundary conditions (2) to (5) is given in [21] in the following form:

$$\theta=\frac{T(r,\tau)-T_0}{T_c-T_0}=$$
$$=K_i\cdot\left[\begin{array}{l}2\sqrt{\frac{R}{r}\cdot Fo}\cdot ierfc\frac{1-\frac{r}{R}}{2\sqrt{Fo}}+\\+\frac{\left(1+3\frac{r}{R}\right)Fo\cdot R^2}{2r\sqrt{R\cdot r}}\cdot i^2erfc\frac{1-\frac{r}{R}}{2\sqrt{Fo}}+\ldots\end{array}\right],\quad (6)$$

where $K_i$ is the dimensionless Kirpichov number:

$$K_i=\frac{q_c\cdot R}{\lambda(T_c-T_0)},\quad (7)$$

$Fo$ – Fourier nuber:

$$Fo=\frac{a\cdot\tau}{r^2}.\quad (8)$$

An integral of errors, with intrinsic properties [21].

$$ierfcx=\int_x^\infty erfc\xi d\xi=\frac{1}{\sqrt{\pi}}e^{-x^2}-xerfcx,$$

$$i^2erfcx=\frac{1}{4}\left[erfcx-2xierfcx\right].\quad (9)$$

Taking into account the low convergence of the series (9) and after substituting equations (7) and (8) into equation (9), we obtain the expression:

$$T(r,\tau)-T_0=\frac{q_c\cdot R}{\lambda}\cdot 2\sqrt{\frac{R}{r}\cdot\frac{a\cdot\tau}{r^2}}\cdot ierfc\frac{1-\frac{r}{R}}{2\sqrt{\frac{a\cdot\tau}{r^2}}}.\quad (10)$$

Let us show that equation (10) is a solution to the boundary value problem (1) to (5). If the temperature is measured in the plane of the heater ($r=R$), it follows from (10):

$$T(r,\tau)-T_0=\frac{2\cdot q_c\cdot\sqrt{a\cdot\tau}}{\lambda\cdot\sqrt{\pi}},\quad (11)$$

since the $ierfc$ function at $x=0$ is: $\pi^{-0.5}$.

The value of the thermal conductivity coefficient is determined by the heat transfer delay time, that is, the time at which the temperature on the surface of the cylinder reaches the same value in the plane of the heater:

$$\Delta T_h(\tau_1)=\Delta T_R(\tau_2),\quad (12)$$

or

$$\frac{q_c\cdot R}{\lambda}\cdot 2\sqrt{\frac{R}{r}\cdot\frac{a\cdot\tau_1}{r^2}}\cdot ierfc\frac{1-\frac{r}{R}}{2\sqrt{\frac{a\cdot\tau_1}{r^2}}}=\frac{2\cdot q_c\cdot\sqrt{a\cdot\tau_2}}{\lambda\cdot\sqrt{\pi}}.\quad (13)$$

After the reduction, we get the following equation:

$$ierfc\frac{1-\frac{r}{R}}{2\sqrt{\frac{a\cdot\tau_1}{r^2}}}=\frac{\sqrt{\tau_2}}{\sqrt{\tau_1\cdot\pi}}\cdot\sqrt{\frac{R^3}{r^3}}.\quad (14)$$

The right-hand side of (14) is known because it includes experimentally measured values.

Using the table, the appropriate value of $B$ can be found, which is an argument of the $ierfc$ function, the value of which allows one to obtain the formula for calculating the thermal conductivity coefficient from the right-hand side of (14):

$$a=\frac{r^2}{4\cdot\tau_2}\left(\frac{1-\frac{r}{R}}{X}\right)^2.\quad (15)$$

To determine the coefficient of thermal conductivity, equation (11) is used:

$$\Delta T_h=\frac{2\cdot q_c\cdot\sqrt{\tau}}{b\cdot\sqrt{\pi}},\quad (16)$$

where $b$ is the coefficient of thermal activity of the wood product, which characterizes the thermal activity of the material, $W\cdot s^{1/2}/(m^2\cdot K)$:

$$b=\frac{\lambda}{\sqrt{a}}=\sqrt{\lambda c\rho},\quad (17)$$

where $c$ is the specific heat capacity of the wood product, kJ/(kg·K);

$\rho$ is the density of the wood product, $kg/m^3$.

Equations (16) and (17) yield the dependence for calculating the coefficient of thermal activity of the product:

$$b=\frac{2q_c\cdot\sqrt{\tau}}{\sqrt{\pi}\cdot\Delta T_h}.\quad (18)$$

The heat flux density is calculated using the formula:

$$q=\frac{U^2}{R\cdot 2S},\qquad(19)$$

where $R$, $U$, $S$ are values of resistance, voltage, and contact area of the heater.

For a cylindrical heater, the contact area will be:

$$S=\pi D\cdot H,\qquad(20)$$

where $D$ is the heater diameter, m;

$H$ is the length of the heater, m.

Then the value of the thermal conductivity coefficient will be:

$$\lambda=b\cdot\sqrt{a}.\qquad(21)$$

The specific heat, in turn, will be determined by the equation:

$$c=\frac{\lambda}{a\cdot\rho}.\qquad(22)$$

Thus, the calculated dependences were derived, which allow obtaining a change in the dynamics of the material's temperature increase during thermal action. At the same time, dependences (15), (17), (21), (22) make it possible to directly calculate the transfer of thermal conductivity in the material depending on the effect of temperature.

**5. 2. Results of determining the temperature through a heat-insulating layer of wood polymer material under thermal influence**

To determine the thermophysical characteristics of the wood polymer material, studies were conducted on its thermal conductivity under the action of a heating device (Fig. 5).

Fig. 5. The process of determining the thermal conductivity of a wood polymer sample under the influence of a heater

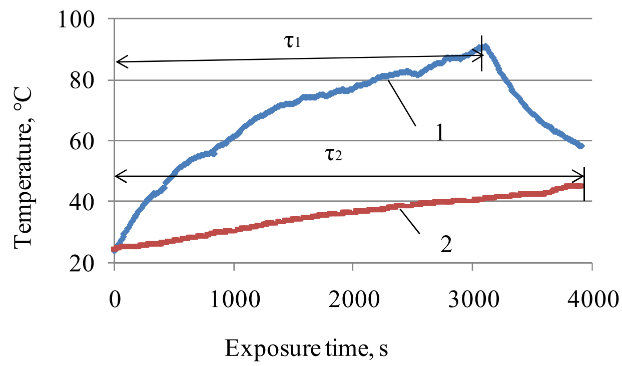



Fig. 6. Results of determining the temperature on the surface of a wood polymer material when heated to 90 °C: 1 — heating curve; 2 — temperature value on the inverted surface of the sample; points $\tau_1$ correspond to the value of the heating curve temperature rise time; $\tau_2$ — in accordance with the value of the temperature rise time on the inverted surface

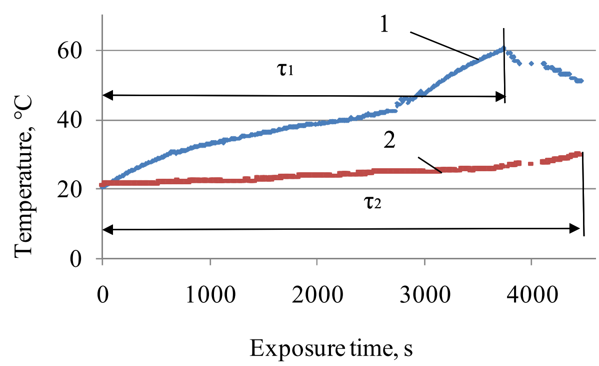



Fig. 7. Results of determining the temperature on the surface of a wood polymer material when heated to 60 °C: 1 — heating curve; 2 — temperature value on the inverted surface of the sample; points $\tau_1$ correspond to the value of the heating curve temperature rise time; $\tau_2$ — in accordance with the value of the temperature rise time on the inverted surface

As can be seen from Table 1, the thermal conductivity of the wood polymer material was within $2.4\div2.9\cdot10^{-8}$ m$^2$/s, the thermal conductivity of the sample did not exceed 0.030 W/(m·K). In addition, the heat capacity of the product corresponds to a value of more than 1034÷1145 kJ/(kg·K) depending on the thickness, which, accordingly, is classified as a heat-insulating material.

The results of studies on determining the temperature and the duration of the induction time of temperature transmission through the layer of the wood polymer material were performed according to the above-mentioned procedure and equipment; the results are shown in Fig. 6, 7.

Based on the results of the measured temperature according to dependence (15), (17), (21), (22), which are given above, the thermophysical characteristics of wood polymer materials were calculated (Table 1).

Table 1

Thermophysical characteristics of a heat-insulating product made of polyurethane foam [22] and wood polymer material

| Material | Thickness, mm | Mass, g | Thermophysical characteristics of heat-insulating products | | | | |
|---|---|---|---|---|---|---|---|
| | | | Density ρ, k/m$^3$ | Heat intensity, W·c$^{1/2}$/(m$^2$·K) | Thermal conductivity, m$^2$/s | Heat transfer λ, W/(m·K) | Heat capacity, kJ/(kg·K) |
| Polyurethane | 10.0 | – | 100 | – | – | 0.029 | 58.8 |
| Wood polymer composite | 8.0 | 36 | 305 | 83.3 | $2.9\cdot10^{-8}$ | 0.031 | 1145.5 |
| Wood polymer composite | 12.0 | 45 | 295 | 77.3 | $2.4\cdot10^{-8}$ | 0.030 | 1034.6 |

Thus, the features of the inhibition of the heat transfer process through the heat-insulating layer made of wood polymer material are explained by the structure of the material in which there is no air movement, which is accompanied by heat transfer. Since the thermal conductivity of the material depends on the volumetric mass, the decrease of which for a wood polymer product leads to a decrease in thermal conductivity. Thus, when using polyurethane foam with a density of 100 kg/m$^3$, the thermal conductivity is 0.029 W/(m·K), which roughly corresponds to the value of the proposed wood polymer material.

## 6. Discussion of results of determining thermal conductivity and strength of wood polymer materials

When studying the process of heat transfer throughout the layer of a wood polymer material, as follows from our results (Table 1, Fig. 6), it is natural to extend the time of temperature transfer through the heat-insulating material. This is due to the formation of a layer of heat-insulating product made of wood-polymer material, that is, the ability of the material to transfer heat. It, in turn, depends on the density of the material, type, size, arrangement of cells with air, etc., which slows down the processes of heat transfer.

It should be noted that the presence of synthetic resin in the polymer material of wood leads to the formation of an elastic layer resistant to mechanical vibrations with sawdust. Obviously, this mechanism of influence of the elastic component is the factor regulating the process of formation of the composite layer, thanks to which the thermal insulation resistance is preserved. In this sense, the interpretation of the results from the determination of the process of inhibition of heat transfer after thermal action, namely the temperature value on the back surface of the sample, is important. Thus, the heat-insulating layer of the wood-polymer material reached a size of about 8 mm, and the temperature on the reverse surface of the sample was 45 °C. This indicates the formation of a temperature barrier, which can be identified by the method of thermal impact on the samples.

This means that taking this fact into account opens the possibility for effective regulation of the properties of the wood polymer material directly in the conditions of serial industrial production.

Comparison of experimental studies on the determination of thermal insulation of wood by polymer material and theoretical assumptions and the resulting calculated dependences made it possible to obtain the change in the dynamics of the increase in temperature of the material under thermal action and to calculate the thermophysical properties of wood polymer material. Since the temperature effect on the sample was 90 °C on the inverted surface under the action of the heat source, it did not exceed 45 °C, and the thickness of the sample was about 8 mm (Fig. 6).

This does not differ from practical data known from works [4, 5], the authors of which, by the way, also associate the effectiveness of heat loss reduction in heat supply systems with the formation of an effective thermal insulation layer. But, in contrast to the results of the studies reported in [23, 24], the data obtained regarding the effect of the heat-insulating coating on the process of inhibiting the transfer of temperature allow us to state the following:

– the main regulator of the thermal insulation process is the density and porosity of the material since high density and low porosity lead to rapid temperature equalization;

– a significant influence on the process of thermal conductivity when using wood material is carried out in the direction of the orientation of the natural material and the properties of the polymer material.

Therefore, the decrease in the density of heat-insulating wood polymer material is associated with the formation of a non-dense structure, which is confirmed in [25]. At the same time, it is possible to polymerize a mixture of synthetic resin and wood sawdust, which reduces the density of the product [26, 27] and at the same time inhibits thermal conductivity. All this increases the environmental friendliness of wood products as there are no chemical substances released and expands the scope of application of wood products. Such conclusions can be considered expedient from a practical point of view because they allow a reasoned approach to resource saving of wood. This allows us to argue about the specifics of manufacturing heat-insulating products from wood for heat insulation, which are certain advantages of this study. From a theoretical point of view, they allow us to assert the definition of the mechanism of the processes of both a decrease in mechanical properties and changes in the heat-insulating properties of a wooden product during thermal insulation, which are certain advantages of this study. Therefore, the practical value of this research is focused on the fact that the results of determining the heat-insulating properties of wood polymer material make it possible to establish the scope of its application.

However, it is impossible not to note that the results of determining the thermal conductivity of wood polymer material (Table 1) indicate an ambiguous effect of a change in the heat-insulating properties of a wood product on heat transfer. This is manifested, first of all, in the increase in the density of the sample during tests of wood polymer material and thermal conductivity. Such uncertainty imposes certain restrictions on the use of the obtained results since the disadvantage for the wood-polymer material is the relationship between its structure and resistance to destruction. The impossibility of removing the mentioned limitations within the framework of this study creates a potentially interesting direction for further research. In particular, they can be focused on detecting the moment of time when the intense decrease in the strength of the wood polymer material begins. Such detection will allow us to investigate the structural transformations of the wood-polymer material, which begin to occur at this time, and to determine the input variables of the process that significantly affect the beginning of such a transformation.

## 7. Conclusions

1. We have modeled the process of heat transfer through a cylindrical heat-insulating layer made of wood polymer material and derived appropriate dependences, which allow obtaining a change in the dynamics of heat transfer and determining thermophysical properties. According to the experimental data and the established dependences, it was found that the thermal conductivity of the wood polymer material was within 2.4÷2.9·10$^{-8}$ m$^2$/s, the thermal conductivity of the sample did not exceed 0.030 W/(m·K). In

addition, the heat capacity of the product corresponds to a value of more than 1034÷1145 kJ/(kg·K) depending on the thickness, which accordingly categorizes it as a heat-insulating material.

2. Features of inhibition of the process of heat transfer through the heat-insulating layer made of wood polymer material are explained by the structure of the product of low density, in which there is no air movement, which inhibits the transfer of heat. Since the thermal conductivity of the material depends on the volumetric mass, the decrease of which for a wood polymer product leads to a decrease in thermal conductivity. Thus, when using polyurethane foam with a density of 100 kg/m$^3$, the thermal conductivity is 0.029 W/(m·K), which roughly corresponds to the value of the proposed wood polymer material.

## Conflicts of interest

The authors declare that they have no conflicts of interest in relation to the current study, including financial, personal, authorship, or any other, that could affect the study and the results reported in this paper.

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## Data availability

All data are available in the main text of the manuscript.

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