

# Investigation of the moisture conductivity of pine wood by trunk height

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**Abstract.** The hydrothermal treatment process is one of the most energy-intensive in wood processing technology, including dewatering and moistening of wood. The hydrothermal treatment process is one of the most energy-intensive in wood processing technology, including dewatering and moistening of wood. The hydrothermal treatment process is one of the most energy-intensive in wood processing technology, including dewatering and moistening of wood. The processes of dewatering or drying of wood are carried out in natural conditions, in drying or steaming chambers. Obtaining a high-quality dried material with minimal internal stresses is possible based on information about the value of the moisture current in the wood, expressed in terms of the moisture conductivity coefficient. The moisture content coefficient depends on the density and humidity of the wood, the direction of moisture flow, temperature, etc. As the temperature rises and the humidity of the wood decreases, the intensity of the moisture current also increases. With a decrease in the moisture content of wood, the value of the diffusion moisture current in it increases. The available information on the moisture content of wood does not take into account the variability of the density of wood in the height of the tree trunk and is presented for the butt part of the trunk. The determination of the moisture conductivity coefficient was established in the radial and tangential directions for sound pine wood, taking into account the height of the trunk by the method of stationary moisture current. Experimentally, an increase in the value of the moisture conductivity coefficient of the pine wood along the trunk height in the radial and tangential directions in the middle part of the trunk by 1.6 times, and in the upper part by 2.05 times compared with the lump. In pine wood, the current intensity in the radial direction is higher than in the tangential direction in wood from the butt part of the trunk by an average of 14.0%, from the middle part of the trunk by 5.0%, and from the apex by 16.0%, regardless of the ambient temperature. The obtained patterns on the variability of the moisture conductivity coefficient of pine wood along the trunk height show the expediency of carrying out preliminary sorting of wood before hydrothermal treatment, taking into account its location in the tree trunk. This will make it possible to optimize the processes of drying and drying of wood, to justify rational modes of chamber and atmospheric drying.

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## 1 Introduction

The technology of wood processing includes a mandatory process of drying or moistening it. These processes are quite energy-intensive and difficult to intensify. The process of removing moisture from wood is one of the primary ones [11]. The process of removing moisture is complex and depends on many factors.

Drying of wood improves its quality, prevents the formability and dimensioning of parts, etc. [6]. It is impossible to carry out the processes of dehydration or humidification of wood without information about the amount of moisture current. An indicator of the intensity of the moisture current is the coefficient of its moisture conductivity. The moisture conductivity coefficient is an indicator that determines the intensity of the moisture current inside the wood. It characterizes the amount of moisture moved per unit of time through a unit area with a difference in moisture concentration of  $1 \text{ kg/m}^3$  and  $1 \text{ m}$  thickness.

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The greatest influence on the movement of moisture in wood is exerted by density, temperature and direction of moisture flow [8], microstructure, etc. It was found in [7, 8, 13, 14, 20] that the porosity of wood increases with an increase in the size of the cavities of the cell walls, more than with a decrease in the viscosity of the liquid, due to an increase in temperature. According to a number of studies, the density and hardness of wood [9, 15, 18], its breed [8, 14, 15], etc. have a decisive influence on the moisture current in wood.

The study of the moisture conductivity of wood is devoted to the work of a number of domestic scientists, of whom the greatest contribution was made by Artsikhovskaya N.V., Alpatkina R.P., Lykov A.V. Sergovsky P.S. of foreign scientists, the works of Martl D.F. and Egner et al. The numerical values of the moisture conductivity coefficient obtained by these scientists allow us to conclude that the moisture conductivity coefficient in the region is below the saturation point of the fiber and can be assumed constant at a constant temperature [8].

The reference literature presents the values of the moisture conductivity coefficient for most of the main tree species growing in the territory of the Russian Federation and of great industrial importance, both in our country and abroad. These values of the moisture conductivity coefficient are given for wood located in the lower part of the trunk at a height of  $1.3 \text{ m}$ . These data on the value of the moisture conductivity coefficient do not take into account the variability of wood density along the trunk height. Studies show that the variability of the density of pine wood growing in the dry forests of the forest-steppe zone of the Russian Federation averages  $1.4\%$  for each meter of trunk height [11]. The decrease in density along the trunk height has one of the determining effects.

Determining the intensity of the moisture current in wood is a complex and labor-intensive process. Therefore, one of the methods currently widely used are modeling methods. A number of theoretical models of diffuse moisture transfer in wood below the saturation point are presented in the scientific literature [1, 5, 17, 19]. The presented models of moisture diffusion are valid within certain limits and have a number of omissions that only approximately take into account the micro- or macrostructure of wood and are based on the assumption of the "elementary cell" of the tracheid [2, 3, 4, 20]. Such an assumption does not ensure the determination of the necessary accuracy of the moisture conductivity coefficient sufficient for carrying out technological processes of dewatering or moistening wood. A

slightly higher accuracy of the moisture conductivity of wood is provided by X-ray methods based on the determination of layered moisture in wood [13]. Indirect methods for determining the moisture conductivity of wood have limitations, which significantly limits their application in practice. The study of the moisture current in wood fibers is important in the construction of drying modes and for small parts and workpieces [4, 12].

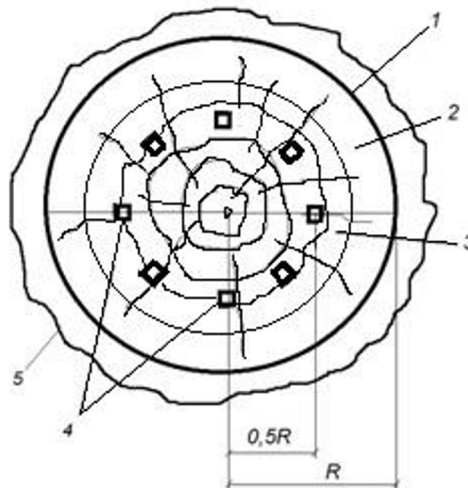
The models presented in the literature do not allow describing the processes of moisture transfer in wood with a given accuracy. These models are based on the assumption of a simplified structure of wood of various tree species. None of the models takes into account the biological variability of the structure of anatomical elements, their size, the presence of defects, position in the trunk of a tree and other equally significant factors affecting the movement of diffuse moisture in wood. Therefore, at present, the task of modeling the process of moisture loss in wood, even for a separate group of rocks, seems extremely difficult.

The simplest and most accurate solution to the problem of determining the value of the moisture conductivity coefficient of wood is the experimental method of stationary moisture flow. In this regard, the purpose of this study is to experimentally determine the value of the moisture conductivity coefficient of pine core wood, taking into account the location of the height of the tree trunk.

## 2 Materials and methods

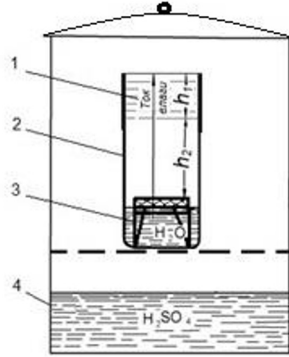
The study of the moisture conductivity coefficient was performed on the wood of the common pine (*Pinussylvestris*L.), growing on the territory of the educational and experimental forestry of the Voronezh State Forestry University named after G.F. Morozov (WALVGLTU) in the Voronezh region. Trees of the same age group were selected for the study.

Discs with a thickness of 40 mm at a height of 0.5 m, 9 m and 18 m were cut from the freshly cut wood of the trunk. Then 8  $30 \times 30 \times 30$  mm samples were cut from each disk at a distance of  $0.5 R$ . The dimensions of the samples were measured with a caliper with an error of  $\pm 0.05$  mm. The diagram of the places where the samples were cut from the disk is shown in Fig. 1. Then all the samples were dried to an absolutely dry state.



**Fig. 1.** Sample sawing scheme: 1) cambium; 2) sapwood; 3) core; 4) sampling sites; 5) bark

The coefficient of moisture conductivity of pine core wood in radial and tangential directions at different trunk heights was determined by the method of stationary moisture flow according to the method proposed by V.N. Artsikhovskaya. The scheme of the pilot plant is shown in Fig. 2.



**Fig. 2.** Installation diagram for determining the moisture conductivity coefficient of wood by the method of stationary moisture current: 1) a sample of wood; 2) a glass with a sample; 3) tripod made of wire covered with gauze; 4) a desiccator;  $h_1$ ) the thickness of the sample;  $h_2$ ) the distance from the gauze to the surface of the sample

The side walls of each of the samples were isolated from contact with the environment (Figure 3). This ensured the moisture flow in the samples in a given direction. After that, each sample was fixed in a glass cup on a thin tin lid. All gaps have been treated with sealant. Part of the glass was filled with distilled water. The intensity of the moisture current in the sample depends on the constant pressure of water vapor at the bottom of the sample. This was achieved by maintaining a constant distance between its lower part and the level of the gauze surface. The sample glasses were then placed in desiccators. To ensure air humidity close to a completely dry state, sulfuric acid was poured into the desiccators, which absorbed moisture vapors. Desiccators with samples were placed in cabinets at temperatures of 20 °C and 60°C.



**Fig. 3.** The appearance of a glass with a sample of wood

As a result of the difference in partial vapor pressures above and below the wood sample, moisture movement occurs. Samples were weighed together with glasses every two days and the weight loss was determined. The moisture passed through the samples was absorbed by sulfuric acid. As moisture was absorbed, sulfuric acid was added to the desiccators to maintain its required concentration. After establishing a constant loss of moisture through the samples, they were removed from the glasses and split into thin plates, the thickness of which was measured by plates with a caliper. Then each plate was weighed and humidity was determined by the weighing method. The moisture gradient  $du/dx$  in the samples was determined graphically.

The numerical values of the moisture conductivity coefficient  $D \cdot 10^{-10}$ ,  $m^2/s$  were determined by the formula

$$D = \frac{M}{F \cdot \rho_o \frac{du}{dx}} \quad (1)$$

where  $M$  – the amount of moisture passed through the wood in 1 second, kg;  
 $F$  – the surface area of the sample perpendicular to the direction of the moisture current,  $m^2$ ;  
 $\rho_o$  – density of wood in absolutely dry condition,  $kg/m^3$ ;  
 $du/dx$  – humidity gradient,  $m^{-1}$ .

### 3 Results

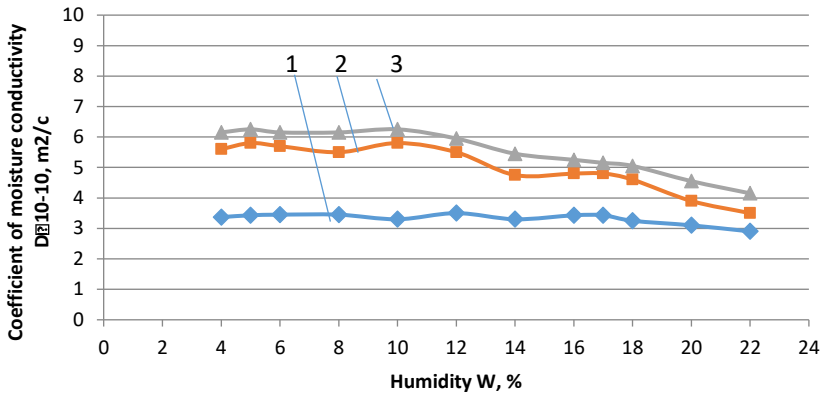
Figures 4 and 5 show the values of the moisture conductivity coefficient of pine core wood, in the radial and tangential directions of the moisture current along the trunk height, depending on its humidity.

The value of the coefficient of moisture conductivity in the radial direction of pine wood along the trunk height at a temperature of 20 °C varies quite significantly. In the butt part of the trunk, the moisture conductivity coefficient of wood varies in the interval  $2.9\text{-}3.4 \cdot 10^{-10} m^2/s$ . A decrease in wood moisture content of less than 17% does not significantly affect the moisture conductivity coefficient, its value is about  $3.4 \cdot 10^{-10} m^2/s$ . An increase in the moisture content of wood over 17% leads to a decrease in the moisture conductivity coefficient to  $2.9 \cdot 10^{-10}$ . A decrease in the moisture content of wood in the middle part of the trunk of less than 10% does not significantly affect the value of the moisture conductivity coefficient, the value of which is on average  $5.7 \cdot 10^{-10} m^2/s$ , and with an increase in humidity above 10% it gradually decreases to  $3.5 \cdot 10^{-10} m^2/s$ . In the upper part of the trunk, the change in the value of the moisture conductivity coefficient is of a similar nature. Thus, when the moisture content of wood is less than 10%, the moisture conductivity coefficient varies within  $6.2 \cdot 10^{-10} m^2/s$ , and when its humidity increases, it monotonously decreases to  $4.2 \cdot 10^{-10} m^2/s$ .

In the tangential direction, the value of the moisture conductivity coefficient of pine wood, at a temperature of 20 °C and a change in humidity, varies more than in the radial direction. Thus, in the butt part of the trunk, the relative stability of the moisture current is noted at a humidity of less than 10% and the moisture conductivity coefficient is on average  $4.3 \cdot 10^{-10} m^2/s$ . With an increase in the moisture content of the wood, the intensity of the moisture current gradually decreases to a value of  $2.3 \cdot 10^{-10} m^2/s$ . In the wood from the middle part of the trunk, the stabilization of the moisture current of about  $4.8 \cdot 10^{-10} m^2/s$  is noted when its humidity is less than 16%. An increase in the importance of wood over 16% causes a decrease in the coefficient of moisture conductivity to  $3.2 \cdot 10^{-10} m^2/s$ . In the upper part of the trunk, if the moisture content of the wood is less than 18%, the moisture current is stabilized. The value of the moisture conductivity coefficient is about  $6.6 \cdot 10^{-10} m^2/s$ . An increase in the moisture content of wood over 18% leads to a decrease in the intensity of the

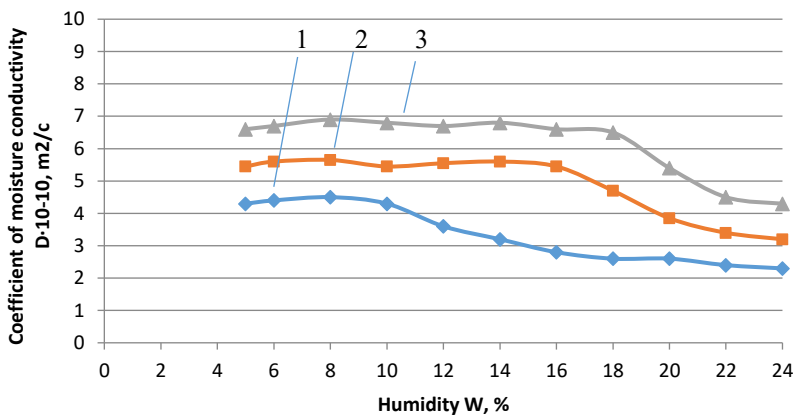
moisture current and the value of the moisture conductivity coefficient decreases to  $4.3 \cdot 10^{-10} \text{ m}^2/\text{s}$ .

The intensity of the moisture current in the radial direction is greater than in the tangential direction in wood from the butt part of the trunk by an average of 14%, from the middle part of the trunk – by 5%, and from the apex – by 16%. It can be noted that regardless of the direction of the moisture current at a temperature of 20 °C, the value of the moisture conductivity coefficient of pine wood increases in trunk height and in the middle part of the trunk by 1.5 times, and from the apex by 2.1 times higher, compared with the lump.



**Fig. 4.** Coefficient of moisture conductivity of pine core wood in the radial direction along the trunk height, depending on humidity at a temperature of 20 °C 1) the butt part of the trunk; 2) the middle part of the trunk; 3) the apex part of the trunk

The coefficient of moisture conductivity of pine wood in the radial direction at a temperature of 60 °C in the butt part of the trunk averages  $9.8 \cdot 10^{-10} \text{ m}^2/\text{s}$ . With a decrease in wood moisture from 22% to 2.5%, the moisture conductivity coefficient increases from  $5.5 \cdot 10^{-10} \text{ m}^2/\text{s}$  to  $13.5 \cdot 10^{-10} \text{ m}^2/\text{s}$ . A slight decrease in the moisture conductivity of wood was noted at a wood moisture content of about 8%.



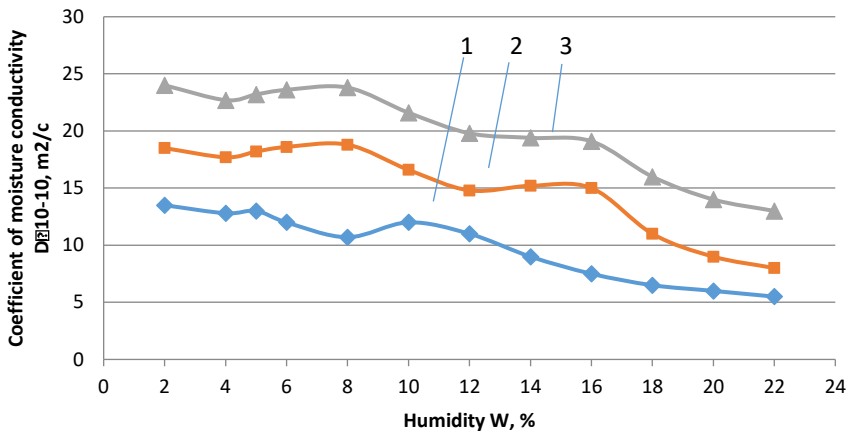
**Fig. 5.** Moisture conductivity coefficient of pine core wood in the tangential direction along the trunk height, depending on humidity at a temperature of 20 °C 1) the butt part of the trunk; 2) the middle part of the trunk; 3) the apex part of the trunk

In the middle part of the trunk, the moisture conductivity coefficient is  $14.9 \cdot 10^{-10}$  m<sup>2</sup>/s, and in the apex  $20.0 \cdot 10^{-10}$  m<sup>2</sup>/s. When the moisture content of the wood decreases from 22% to 2%, the intensity of the moisture current in the wood from the middle part of the trunk increases from  $8 \cdot 10^{-10}$  m<sup>2</sup>/s to  $18.5 \cdot 10^{-10}$  m<sup>2</sup>/s, and in the apex - from  $13 \cdot 10^{-10}$  m<sup>2</sup>/s to  $24 \cdot 10^{-10}$  m<sup>2</sup>/s. Relative stabilization of the moisture current was observed in wood from the middle and upper parts of the trunk in the humidity range of 12-16%, as well as less than 8% in the butt part of the trunk.

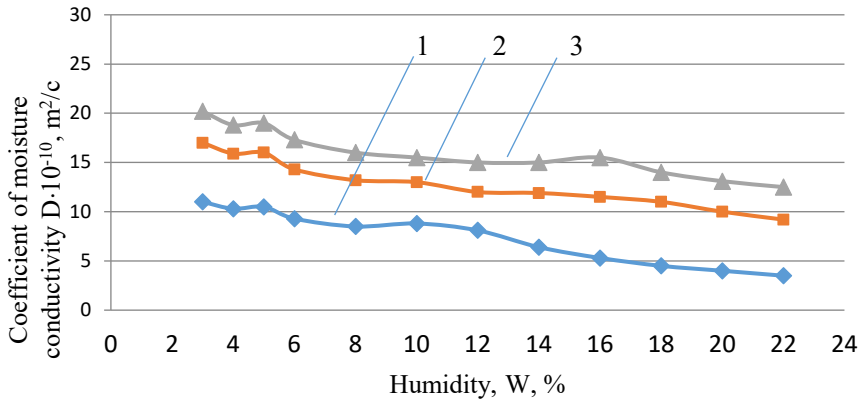
In the tangential direction, the moisture conductivity coefficient of pine wood from the butt part of the trunk at a temperature of 60 °C averages  $7.5 \cdot 10^{-10}$  m<sup>2</sup>/s, in the average -  $13.0 \cdot 10^{-10}$  m<sup>2</sup>/s, and in the apex  $16.0 \cdot 10^{-10}$  m<sup>2</sup>/s. With a decrease in wood moisture from 22% to 2%, the moisture conductivity coefficient in the butt part of the trunk increases from  $3.5 \cdot 10^{-10}$  m<sup>2</sup>/s to  $11.0 \cdot 10^{-10}$  m<sup>2</sup>/s, in the middle - from  $9.2 \cdot 10^{-10}$  m<sup>2</sup>/s to  $17.0 \cdot 10^{-10}$  m<sup>2</sup>/s, and in the apex - from  $12.4 \cdot 10^{-10}$  m<sup>2</sup>/s from up to  $20.2 \cdot 10^{-10}$  m<sup>2</sup>/s.

The intensity of the moisture current at a temperature of 60 °C in the radial direction is greater than in the tangential direction in wood from the butt part of the trunk by an average of 14.0%, from the middle part of the trunk – by 5.0%, and from the apex – by 16.0%, which corresponds to the values of the moisture current at a temperature of 20 °C. It can be noted that at temperatures of 20 °C and 60 °C, regardless of the direction of the moisture current, the patterns of change in the moisture conductivity coefficient in pine wood are identical in trunk height. An increase in the ambient temperature from 20 °C to 60 °C increases the intensity of the moisture current in the wood in the radial direction by an average of 2.8 times, and in the tangential direction by 2.5 times.

The average value of the moisture conductivity coefficient along the trunk height is of practical importance. An increase in the moisture current in the wood along the trunk height has been experimentally established. The average value of the moisture conductivity coefficient, in the radial and tangential directions, increases in the middle part of the trunk by 1.6 times, and in the apex by 2.05 times compared with the butt part of the trunk.

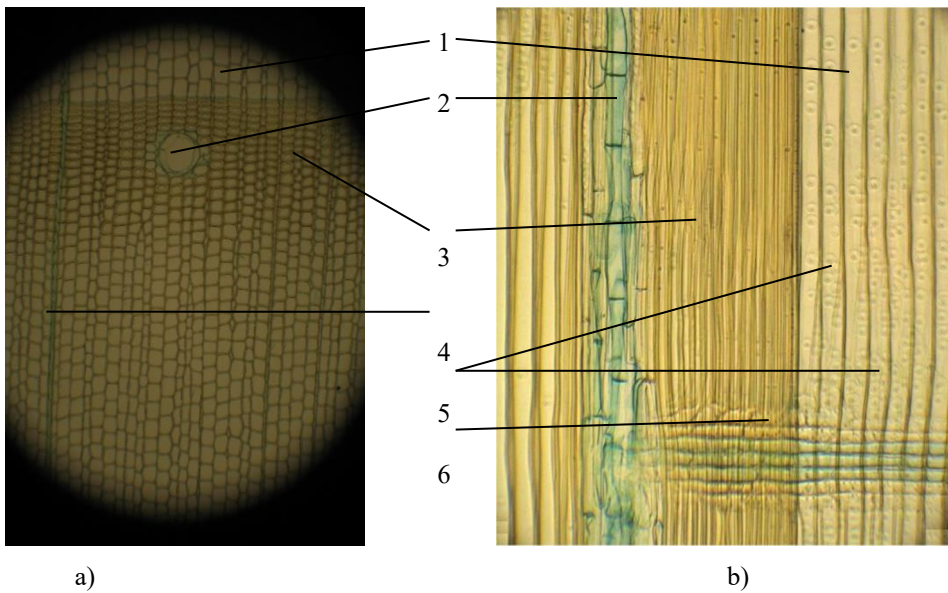


**Fig. 6.** Coefficient of moisture conductivity of pine core wood in the radial direction along the trunk height, depending on humidity at a temperature of 60 °C 1) the butt part of the trunk; 2) the middle part of the trunk; 3) the apex part of the trunk

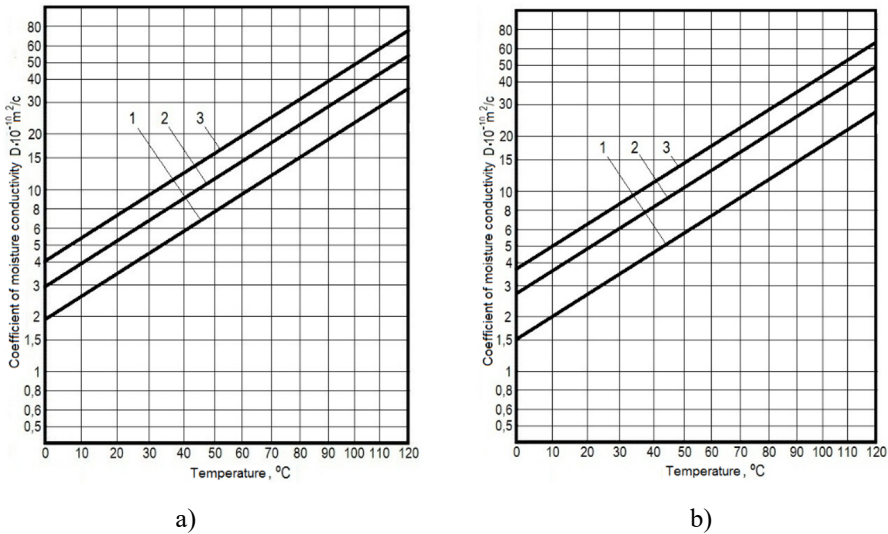


**Fig. 7.** Moisture conductivity coefficient of pine core wood in the tangential direction along the trunk height, depending on humidity at a temperature of 60 °C 1) the butt part of the trunk; 2) the middle part of the trunk; 3) the apex part of the trunk

For engineering calculations, the values of the moisture conductivity coefficient of pine wood, depending on temperature, are presented in the form of graphs in Fig. 9.



**Fig. 8.** Cross section of intact (a) and fire-damaged (b) pine wood: 1) early wood; 2) resin stroke; 3) late wood; 4) core beam; 5) tarred wood; 6) radial trachea



**Fig. 9.** The coefficient of moisture conductivity of pine core wood in the radial (a) and tangential (b) directions along the trunk height: 1) the butt part of the trunk; 2) the middle part of the trunk; 3) the apex part of the trunk

## 4 Discussion

The analysis of the results of the study of the moisture conductivity of pine wood at a temperature of  $20^{\circ}\text{C}$  shows that the intensity of the moisture current in the radial direction in the butt part of the trunk practically does not depend on the moisture content of the wood. A decrease in the moisture content of wood of less than 10-12% leads to an increase in the moisture current in the middle and upper parts of the trunk by more than two times, compared with the butt part of the trunk. With a decrease in the humidity of the wood in the butt part of the trunk, the moisture current in the tangential direction increases approximately twice, achieving some stabilization at a humidity of 10% or less. In the middle and upper part of the trunk, it reaches its greatest value with a wood moisture content of less than 16-18%.

The difference in the intensity of the moisture current in the wood in the radial and tangential directions is due to the structure of the anatomical elements. The greater movement of moisture in the radial direction is due to the presence of core rays and radial tracheids (Fig. 8). Their uniform distribution in the trunk of the tree contributes to a more uniform flow of moisture in this direction.

In the tangential direction, moisture movement occurs mainly through the bordered pores. The movement of moisture through these pores is often complicated by the displacement of the tori and the overlap of the pore channels. In the lower part of the trunk, the number of bordered pores with an offset torus is higher. With an increase in the height of the trunk, the number of pores with an offset torus decreases slightly. This leads to stabilization of the moisture current in the tangential direction (fig. 5, pos. 2 and 3).

Its density has a great influence on the moisture conductivity of wood. In the butt part of the trunk, the density of wood is the highest. With an increase in the height of the trunk, the density of the wood decreases and, as a result, its porosity increases. A decrease in density has a decisive effect on increasing the intensity of moisture flow in wood at low temperatures.

The nature of the change in the moisture conductivity coefficient of wood from different parts of the tree trunk should be taken into account during atmospheric drying. The intensity of the moisture current in pine wood in the radial direction at a temperature of  $20^{\circ}\text{C}$  in the

butt part of the trunk changes slightly with a change in the moisture content of the wood, compared with the moisture current in the middle and upper parts of the trunk. The value of the moisture conductivity coefficient of pine wood in the tangential direction is less than in the radial direction, by about 12%. The intensity of atmospheric drying of round timber from the butt of the trunk will be less than from the middle and upper parts of the trunk, all other things being equal, by about 1.5 times. It seems advisable to place timber from the middle and upper parts of the trunk in separate stacks and maintain a higher moisture evaporation rate when atmospheric drying of wood to a moisture content of less than 18%. During atmospheric drying, it is also possible to lay lumber in the form of boards from the butt of the trunk into separate stacks.

The most effective pre-sorting of lumber before atmospheric drying will be in the regions belonging to the fourth climatic zone. In these regions, the warm season exceeds the cold, and the average annual temperature is quite high. This ensures relatively rapid removal of moisture from the wood. Compared to other climatic zones, the process of drying wood to a moisture content of 10% is economically advantageous.

Temperature rise from 20 °C to 60 °C. it causes an increase in the moisture current in the wood, approximately twice the entire height of the trunk, but in the lumpy part it is less than from the middle and apex. In this regard, it also seems advisable to carry out preliminary sorting of lumber and stacking them in separate stacks. This will make it possible to use the work of the drying chambers more efficiently and increase their productivity by 1.5-2.0 times.

The possibility of intensifying the drying chamber process is of great practical importance. An analysis of the value of the moisture conductivity coefficient of wood shows that multi-stage drying modes are most acceptable for drying pine wood. The recommended RTM modes of the third stage from the initial moisture content of wood of 25% are not rational. It seems advisable to divide the third stage into areas with a wood moisture content of 25-15%, 15-10% and less than 10%.

As the temperature increases, the difference in the intensity of the moisture current in the radial direction increases compared to the tangential one. When drying bars or beams, this will reduce the duration of the drying process somewhat more than when drying lumber in the form of boards.

## **5 Conclusion**

The density of pine wood decreases along the height of the trunk, and therefore, the intensity of the moisture current changes.

In pine wood, the intensity of moisture flow in the trunk in the radial direction is higher than in the tangential direction in the butt part of the trunk by an average of 14.0%, from the middle part of the trunk – by 5.0%, and from the apex – by 16.0%, regardless of the ambient temperature.

The intensity of the moisture current in the wood increases in the radial direction by 2.8 times, and in the tangential direction by 2.5 times when the temperature rises from 20 °C to 60 °C.

The value of the moisture conductivity coefficient increases in the middle part of the trunk by 1.6 times, and in the apex - by 2.05 times compared with the lump, regardless of the direction of the moisture current.

The patterns of changes in the value of the moisture conductivity coefficient depending on the moisture content of the wood will allow you to adjust the existing atmospheric and chamber drying modes, increase the rate of moisture flow and reduce the amount of residual stresses in the wood.

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