Formation of density and porosity of pine wood in a tree trunk

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Abstract. Wood is a material with unique properties that contribute to its wide use as a raw material for various types of industries. Different quality requirements are imposed on the raw material depending on the material or wood product. However, physical and mechanical properties of wood are not homogeneous along the radius and height of the trunk and depend on the species, location in the trunk and growing conditions. The aim of this research is to study the variability of porosity and density of Scots pine (Pinus sylvestris L.) wood in a tree trunk growing in dry forests of the forest-steppe zone of the Russian Federation. The studies were carried out on wood cuts, sawn at different trunk heights. The change in the density of pine wood along the height of the trunk by 1.43% for each meter has been established. The wood porosity increases from the butt to the top by an average of 5.5%. New information about the variability of wood properties makes it possible to rationally and reasonably approach the choice of raw materials for obtaining materials with specified performance characteristics.

1. Introduction

Wood is a material of biological origin, which is characterized by variability of properties. This is due to the peculiarities of the biological development of the tree in ontogenesis. The properties of wood vary both in height and in the section of the trunk. Variability indicators are greatly influenced by the species and growing conditions of a tree [1].

Density is one of the most important physical properties of wood. It is an indicator of the technical properties of wood. Commercial grade of wood is directly dependent on the density of feedstock [2]. Another important physical property of wood is porosity. Porosity characterizes relative volume of voids in absolutely dry wood, formed by cell lumens, intercellular spaces and sections of cell walls. As the wood cellwall density is more or less constant (1.5 g/cm³) within a wood species [3], the density of wood depends on its porosity.

According to the currently valid standards in Russia, only visual sorting of raw materials is provided, which does not take into account physical and mechanical properties of wood and their variability in the tree trunk [4]. Variability of wood properties must be taken into account when crosscutting and subsequent sorting of raw materials. Pre-sorting will make it possible to select raw materials with homogenous physical and mechanical properties and to manufacture products with specified quality...
indicators.

Over the past few decades, a number of studies have been devoted to the formation of wood density and porosity. Growing conditions have a great influence on the formation of wood density along a tree trunk [5-7]. The formation of wood density depends on the spacing of trees, their age and growing conditions. Tree spacing in stands at an early age has the greatest influence on the density value. High wood density can be formed in plantations due to the density of tree planting [8]. With an increase in the age of the stands, the influence of the stand density and their growth class on the formation of wood density in the tree trunk decreases [9-11]. The density formation is influenced by a mixture of stands of different species [12]. Regulation of wood density through forestry activities at a later age depends on the growing conditions and climatic zones and it is more effective in unfavorable conditions of the forest-steppe zone.

Climatic conditions have a great influence on the formation of density, especially at an early age. The formation of wood density in the northern and middle part of the taiga depends on latitudinal zoning and climatic region; the effect of tree spacing and plantation growth class does not significantly affect the formation of wood density at maturity age [13,14]. Tree spacing has a significant effect on the formation of wood density in the tree trunk in less favorable growing conditions in the forest-steppe zone and in the continental and temperate continental climates. The variability of weather conditions is a determining factor in the tree growth in the forest-steppe [1,9,13]. An increase in latitudinal zoning contributes to an increase in the density of wood in stands in the area of the monsoon climate, in the area of the same zoning (eastern regions of the Russian Federation) [15].

Density of wood in a tree trunk is unevenly distributed and decreases from the butt to the top and along the radius of the trunk. Density variability along the trunk height is present in any tree trunk, but its value is individual for different species [1,5,16-18]. Changes in density along the radius of the trunk can follow four models: 1 – density decrease in the middle of the radius of the trunk; 2 – increased density in the middle part of the trunk radius; 3 – density increase from core to bark; 4 – decrease in density from core to bark. In pine plantations growing in the north of the European part of Russia with a temperate maritime climate, the density change along the trunk radius in 67% of cases occurs according to the 2nd model [6]. Information about the nature of the distribution of the wood density in the trunk of a pine growing in the forest-steppe zone under adverse conditions is insignificant.

The most of the researchers studied wood density in the tree trunk on wood, cut from the trunk at a height of 1.3 m from the butt. Density distribution of pine wood along the height of the tree trunk is presented in the studies for the taiga zone with favorable growing conditions.

The purpose of this work is to study the variability of the density and porosity of pine wood in a tree trunk using the example of forest stands in the forest-steppe zone of the Voronezh region. More detailed knowledge of this variability in density and porosity can help improve the assessment of wood quality. Information about the regularity of the formation of pine wood density and porosity in the tree trunk enables to approach a reasonable choice of raw materials for obtaining products with required performance characteristics.

2. Experimental part
The study of the formation of density and porosity was carried out on the coniferous wood of Scots pine (Pinus sylvestris L.). Pine wood specimens were taken at Educational and Experimental Forestry Enterprise of Voronezh State University of Forestry and Technologies, Voronezh Region (52°N and 39°E) under the conditions of the southern border of the forest-steppe zone located in an area of temperate continental climate.

The study of the formation of wood density and porosity in a tree trunk was carried out on the specimens cut from model pine wood trees. The selection of model trees was made in accordance with [19]. Sixteen model trees were selected on the trial plot. The average length of the long-length stems under study was 18 m, the average diameter at the top end was 32 cm, and at the butt end it was 52 cm.

From each model tree, cross-sections of wood were prepared in the form of disks with the thickness of 3.5 cm, sawn at a distance of 0.1, 3, 6, 9, 12, 15, and 18 m from the butt end. Bark with a bast layer
was removed from the surface of the discs, and blanks with a length equal to its diameter and 50 mm wide were cut out from the central part of each disc. Clean small specimens 30 mm high and with a 20×20 mm base were made from each blank, at a distance of 0.1R, 0.3R, 0.5R, 0.7R, and 0.9R. One of the specimen axes should be along the wood fibers. Annual layers on the end surfaces of the specimens were parallel to one pair of opposite faces and perpendicular to the other one. Sampling was carried out by one-stage sampling. The minimum number of specimens was determined taking into account the coefficient of variation for wood density which is equal to 10%.

The density of wood was determined in accordance with [20]. The density of wood in an absolutely dry state was determined after drying the specimens in a drying chamber (SHS-80-01 SPУ, Smolenskoye SKTB SPU, 2020) at a temperature of 103±2 ºС. After that, the specimens were cooled in a desiccator, on the bottom of which concentrated 94% sulfuric acid (Stegler, China) was poured. After cooling down, the specimen sizes were determined using a ShSH-1 caliper with an error of no more than 0.02% and the weight of the specimens on a scale (OHAUS AR 5120, OHAUS, 2015) brand with an error of no more than 0.01 g.

The porosity (P) of wood was determined by calculation using the formula:

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P = \left(1 - \frac{\rho_s}{\rho_{w.s.}}\right) \cdot 100\%
\]

where \(\rho_s\) and \(\rho_{w.s.}\) – density of the specimen and woody substance contained in it, respectively, kg/m\(^3\).

3. Results and discussion
The results of experimental studies of changes in the density of pine wood along the radius of the trunk at different heights (figure 1) and along the height of the trunk (figure 2).

**Figure 1.** Density of pine wood along the radius of the trunk at different heights at normalized moisture content of 12%. 1, 2, 3 – density of wood in the butt at a height of 0.1 m (1); middle 9 m) (2) and top part of the trunk 18 m (3).

**Figure 2.** Density of pine wood along the height of the trunk at normalized moisture content of 12%. Density at 0.1R (1), 0.5R (2), 0.9R (3) fraction of the trunk radius.

Density of pine wood increases from the central part to the bark (surface) along the radius of the trunk. This pattern can be traced along the entire height of the trunk. The greatest increase in density along the trunk radius is in the butt (at a height of 0.1 m) and in the top part of the trunk (at a height of 18 m) and averages 63%. The maximum density increase in the butt part occurs in the 0.1-0.5R section, and in the top of the trunk, in the 0.5-0.9 R section. In the middle part of the trunk, the density of wood along the radius of the trunk increases uniformly from the center to the periphery and averages 28%. Average density in the top part of the trunk is 433.95±3.54 kg/m\(^3\), in the middle - 417.15±3.54 kg/m\(^3\), and it is 443.53±3.54 kg/m\(^3\) in the butt part.

Wood density from the butt to the top decreases uniformly to a height of 15-16 m by an average of 27%. This is the highest quality commercial timber. The decrease in density in this area is on average
6.91 kg/m³ per meter, or 1.43%. Wood density increases by 19% being closer to the crown at a height of 16-18 m. The most intense increase in wood density in this area occurs in the peripheral part of the trunk. Decrease in wood density from the butt to the top along the entire height of the trunk is insignificant and does not exceed 4.5% in the central part of the trunk.

The results of experimental studies of changes in the porosity of pine wood along the radius of the trunk at different heights are shown in figure 3.

Figure 3. Porosity of pine wood along the radius of the trunk at different heights. Porosity of wood in the butt at a height of 0.1 m (1), middle 9 m (2) and top part of the trunk 18 m (3).

Porosity of pine wood decreases from the central part to peripheral one. The magnitude of the decrease in density along the radius of the trunk is different. And it is about 78±0.08% in the central part over the entire height of the trunk, then (to the peripheral part of the radius of the trunk) it decreases to 66% in the butt part, 71% – in the middle, 62% – in the top. The average porosity in the top part of the trunk is 71.5±1.05%, in the middle – 72.74±0.38%, and it is 70.94±0.83% in the butt part.

Figure 4 shows the change in the average porosity of pine wood along the height of the trunk. Porosity of wood increases in the trunk from the butt to the top in the commercial part of the trunk to a height of 16 m by an average of 5.5%. At a height of over 16 m, wood porosity is significantly reduced, mainly due to the peripheral zone of the trunk, along the radius of the trunk by 5% on average. The porosity of core wood in the central part of the trunk along its entire height remains practically unchanged within 78%.

4. Conclusions
Density of pine wood in the forest-steppe zone in a temperate climate decreases from butt to top by an average of 1.43% per meter. A significant increase in the density of pine wood occurs near the crown. The greatest variability of density along the trunk radius is in the butt and top parts of the tree. The distribution of the density of wood along the radius of the trunk in the plantations of the southern border of the forest-steppe zone located in the region of the temperate continental climate differs significantly from the nature of density distribution in the plantations of the taiga zone with a greater latitudinal zoning. A decrease in latitudinal zoning and tightening of growing conditions cause a shift in the maximum density of pine wood from bark to core along the trunk height (by 15-20%) [1].

In a tree trunk, porosity increases from the butt to the top in the commercial timber zone to the crown by 5.5%. At the crown, the porosity of wood is significantly reduced due to the peripheral zone. The central part of the trunk (core wood) has the highest porosity, (about 78%) and the peripheral part shows the lowest one.

New information on the regularity of the density and porosity formation of pine wood in the tree trunk makes it possible to reasonably make the choice of raw materials for obtaining products with increased performance characteristics.
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