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The Results of Experimental Studies of the Apparent Density of Wood

Renat Kh. Gainullin[1]✉***, Candidate of Engineering, Assoc. Prof.;*** *ResearcherID: MIQ-8343-2025, ORCID: https://orcid.org/0000-0002-2492-8861*
Ruslan R. Safin[2]***, Doctor of Engineering, Prof.;*** *ResearcherID: O-9355-2015, ORCID: https://orcid.org/0000-0002-0226-4232*
Albina V. Safina[2]***, Candidate of Engineering, Assoc. Prof.;*** *ResearcherID: CAA-1333-2022, ORCID: https://orcid.org/0000-0002-7344-9242*
Rishat Kh. Gainullin[1]***, Candidate of Engineering, Assoc. Prof.;*** *ResearcherID: MIT-0804-2025, ORCID: https://orcid.org/0000-0003-2219-2413*
Ekaterina M. Tsvetkova[1]***, Postgraduate Student;*** *ResearcherID: MIQ-9779-2025, ORCID: https://orcid.org/0000-0002-5664-5866*
[1]Volga State University of Technology, pl. Lenina, 3, Yoshkar-Ola, 424000, Russian Federation; gainyllinrh@yandex.ru✉, rishat_000@mail.ru, Ekaterinadudina@mail.ru
[2]Kazan National Research Technological University, ul. K. Marksa, 68, Kazan, 420015, Russian Federation; cfaby@mail.ru, alb_saf@mail.ru

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Abstract. The article presents the results of experimental studies of the apparent density of wood obtained under various operating modes of the pneumatic measurement system. A new technique and experimental unit have been used for the research to determine the apparent volume of porous bodies in an atmospheric air environment. For the experiments, samples of aspen, spruce, birch, pine and oak wood taken from the sapwood of tree stems have been used. The functional stability of the developed method for determining the apparent volume of porous bodies has been experimentally confirmed. Using the developed experimental unit, the apparent volumes have been measured and apparent densities of wood samples of various species have been calculated under conditions of overpressure and underpressure of the system operation. In the overpressure mode, the pneumatic system has operated at +70 and +90 kPa, and in the underpressure one at –70 and –90 kPa, respectively. It has been experimentally established that when operating the measurement system in the underpressure mode, the apparent density of wood is higher than in the overpressure mode. The values of apparent densities determined in the underpressure mode vary within the range of 1.361 to 1.434 g/cm^3 for aspen, 1.151 to 1.348 g/cm^3 for spruce, 1.356 to 1.402 g/cm^3 for birch, 1.298 to 1.444 g/cm^3 for pine and 0.99 to 1.147 g/cm^3 for oak. The corresponding values of apparent densities determined in the overpressure mode have been 1.316 to 1.372 g/cm^3 for aspen, 1.106 to 1.274 g/cm^3 for spruce, 1.292 to 1.356 g/cm^3 for birch, 1.285 to 1.412 g/cm^3 for pine and 0.904 to 1.138 g/cm^3 for oak. Thus, the hypothesis about the priority of applying the underpressure mode when determining the apparent volume of porous bodies in the atmospheric air environment has been confirmed. The magnitude of the largest deviation between the highest and lowest values of apparent density when determined in different modes has been, respectively: for aspen – 6.83 %, for spruce – 8.54 %, for birch – 6.35 %, for pine – 6.82 % and for oak – 3.91 %. The magnitude of the largest deviation between the maximum values of apparent density and the generally accepted value of 1.46 g/cm^3 have been, respectively: for aspen – 1.78 %, for spruce – 7.67 %, for birch – 3.97 %, for pine – 1.1 % and for oak – 21.44 %.

Keywords: wood, apparent density, measurement system, measurement modes, overpressure, underpressure

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Научная статья

Результаты экспериментальных исследований кажущейся плотности древесины

Рен.Х. Гайнуллин[1]✉***,*** *канд. техн. наук, доц.; ResearcherID: MIQ-8343-2025, ORCID: https://orcid.org/0000-0002-2492-8861*
Р.Р. Сафин[2]***,*** *д-р техн. наук, проф.; ResearcherID: O-9355-2015, ORCID: https://orcid.org/0000-0002-0226-4232*
А.В. Сафина[2]***,*** *канд. техн. наук, доц.; ResearcherID: CAA-1333-2022, ORCID: https://orcid.org/0000-0002-7344-9242*
Риш.Х. Гайнуллин[1]***,*** *канд. техн. наук, доц.; ResearcherID: MIT-0804-2025, ORCID: https://orcid.org/0000-0003-2219-2413*
Е.М. Цветкова[1]***,*** *аспирант; ResearcherID: MIQ-9779-2025, ORCID: https://orcid.org/0000-0002-5664-5866*
[1]Поволжский государственный технологический университет, пл. Ленина, д. 3, г. Йошкар-Ола, Россия, 424000; gainyllinrh@yandex.ru✉, rishat_000@mail.ru, Ekaterinadudina@mail.ru
[2]Казанский национальный исследовательский технологический университет, ул. К. Маркса, д. 68, г. Казань, Россия, 420015; cfaby@mail.ru, alb_saf@mail.ru

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Аннотация. Приведены результаты экспериментальных исследований кажущейся плотности древесины, полученные при различных режимах функционирования пневматической системы измерения. Использовали новую методику и экспериментальную установку для определения кажущегося объема пористых тел в среде атмосферного воздуха. Образцы древесины отбирали из заболонной части стволов осины, ели, березы, сосны и дуба. Экспериментально подтверждена практическая пригодность предложенного метода. С помощью разработанной экспериментальной установки измерены кажущиеся объемы и рассчитаны кажущиеся плотности древесных заготовок различных пород при режимах избыточного давления и разрежения функционирования системы. В режиме избыточного давления пневматическая система работала при +70 и +90 кПа, а в режиме разрежения – при –70 и –90 кПа. Экспериментально установлено, что при эксплуатации измерительной системы в режиме разрежения кажущаяся плотность древесины выше, чем при эксплуатации системы в режиме избыточного давления. Кажущаяся плотность, определенная в режиме разрежения, изменяется в пределах

1,361–1,434 г/см³ для осины, 1,151–1,348 г/см³ для ели, 1,356–1,402 г/см³ для березы, 1,298–1,444 г/см³ для сосны, 0,99–1,147 г/см³ для дуба. Кажущаяся плотность, установленная в режиме избыточного давления, составила 1,316–1,372 г/см³ для осины, 1,106–1,274 г/см³ для ели, 1,292–1,356 г/см³ для березы, 1,285–1,412 г/см³ для сосны, 0,904–1,138 г/см³ для дуба. Таким образом, подтверждается гипотеза о приоритете применения режима разрежения при измерении кажущегося объема пористых тел в среде атмосферного воздуха. Наибольшее отклонение между максимальной и минимальной кажущимися плотностями при разных режимах составило: осина – 6,83 %, ель – 8,54 %, береза – 6,35 %, сосна – 6,82 %, дуб – 3,91 %. Наибольшая разница между максимальной кажущейся плотностью и общепринятой 1,46 г/см³ равнялась: осина – 1,78 %, ель – 7,67 %, береза – 3,97 %, сосна – 1,1 %, дуб – 21,44 %.

Ключевые слова: древесина, кажущаяся плотность, измерительная система, режимы измерения, избыточное давление, разрежение

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Introduction

All the materials used by people in their everyday life have different physical and mechanical properties. The most common and universal physical quantity used for characterizing the properties of a material is its density. However, the density of the same material may vary within a great range. This is true for porous materials whose density may be described as average and true. Wood with various types of density also belongs to porous materials [12]. Generally, the technological calculation practice applies a value of the average density of wood. However, this value varies within a great range not only for the same species but also for the same tree [14]. It should be noted that the most precise measure of wood content in the volume unit of a material is the true density of wood. In wood science, it is called wood substance density [23]. Currently, it is generally accepted that the wood substance density is 1.53 g/cm³. Wood is a capillary-porous material of plant origin, consisting of cell walls, which is why the concept of cell wall density is used in wood science. In his work O.I. Poluboyarinov [16] notes that the density of cell walls and the density of wood matter differ by approximately 10 %. This discrepancy indicates the presence of a significant volume of micropores (second-order pores) in the cell walls. In addition to the true density and the density of the cell walls, foreign authors are also using the concept of an apparent density of wood. The apparent density is the ratio of the mass of a sample to its volume, including the volume of closed pores (if any), and excluding the volume of open pores and cavities between the particles of the sample in a bulk material. In our understanding, if there are no closed pores in the wood samples being studied, the apparent density will be equal to the density of the cell walls.

One of the earliest methods of measuring the true density of wood is the suspension method [5, 8, 19]. According to this method, prepared wood samples are inserted into solutions of different salts. After the wood gets saturated, the solution density is adjusted so that the samples are suspended in the solution. It indicates that the densities of the solution and the wood sample are equal. Consequently, the wood density can be defined by a numerical value of the solution density. The above mentioned researchers have carried out the experiments and obtained the wood density values from 1.4 to 1.56 g/cm^3 depending on the species. It should be noted that this method takes significant amounts of time and labour, therefore nowadays it is used rather seldom.

In the beginning of the 20th century, the pycnometry method has started being used for measuring the density of a material. This method can be summarized as follows: a body immersed in any medium displaces from it a volume which is equal to the volume of this body. Such liquids as water, alcohol, petrol, toluene, etc. and gases like helium, oxygen, nitrogen, hydrogen, etc. have been used as displacement media [1, 2, 18, 20, 22]. The numerical values of density obtained by the pycnometry method have varied depending on the medium used. So, the density measured in water has been on average 1.54 g/cm^3, while that one measured in the gas medium has been 1.46 g/cm^3.

Another method of measuring the cell-wall density of wood, the mercury porosimetry method, is similar in concept but different in its procedure. In this case, mercury is discharged into the pores of wood under high pressure [13, 15, 21]. The density measured via this method is about 1.43 g/cm^3. This method cannot become common due to the toxicity of mercury and to the fact that the wood samples cannot be used for further research as well as in the case of applying the suspension method because such samples contain mercury and salts.

The above mentioned methods of measuring the cell-wall density are classified as direct methods. In addition to them, there is one more indirect method, which is the optical (planimetric) method. It helps define the cell-wall density value by the relation of the density of the whole volume of wood and the percentage content of cell walls in a measured sample. To apply this method, a microsection of wood is made, and then its weight, dimensions, and average density are measured. After that, its image is zoomed by a microscope, and the area taken by cell walls in the area of the whole section is measured by a planimeter [3, 7, 10, 17, 24]. According to the experimental data obtained, the cell-wall density measured by the planimetric method is within 1.02 to 1.30 g/cm^3 for various wood species. At the present time, this method is improved due to the use of radiography and computer tomography [11] for producing high resolution images of a wood microsection.

Nowadays, among the above mentioned methods of measuring the cell-wall density, the most commonly applied method is the helium pycnometry standardized by many countries of the world [4, 9]. Beside its advantages, this method also has its drawbacks which could include the requirement to helium grade and the necessity for a multi-stage calibration procedure to be implemented only in the overpressure mode of a measurement pneumosystem.

Currently, the researchers show less and less interest for the investigations of the cell-wall density of wood. First of all, it can be explained by the difficulty of developing new methods for measuring the cell-wall density of wood. The second important factor is that certain amount of knowledge about this value has already been accumulated. Nevertheless, modern science needs new methods and approaches in order to gain new knowledge in this field. Moreover, an essential issue is the equality of the cell-wall density of wood and its apparent density.

This paper presents 2 interconnected aspects. Firstly, an alternative method of gas pycnometry using the atmospheric air instead of helium as a measurement medium has been proposed and tested. Secondly, the comparative data on the cell-wall density and the apparent density of various species have been presented.

Research Objects and Methods

In order to eliminate the shortcomings of the existing method of gas pycnometry, the authors have proposed an alternative technique of measuring the apparent density of wood [6]. This method applies the atmospheric air instead of helium in a pneumatic measurement system. For experimental studies, we have developed a unit (Fig. 1) consisting of 2 cylinders *1*, *6* of equal capacities, valves *3*, *4*, *5*, *12*, a pneumatic pump *13* with a manometer *14* and a relief valve *15*, cylinders *11* containing water and series-connected with the unit by transparent pipe lines *9*, *10* with scales *7*, *8*. The volume and density of porous bodies can be measured via this method when the measurement system operates in the overpressure and underpressure modes.

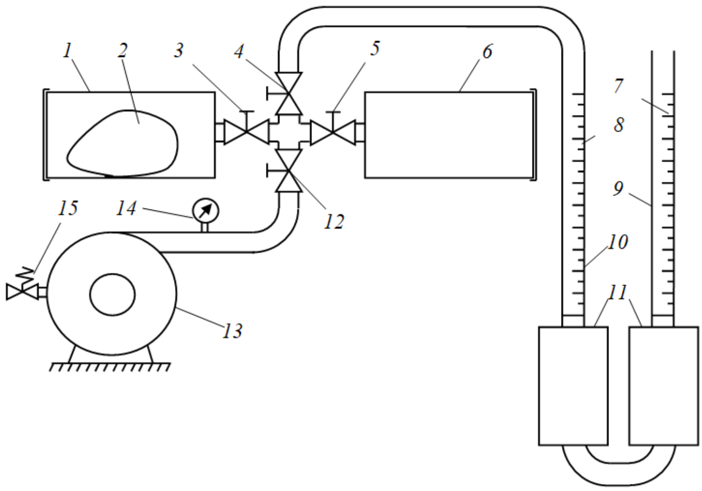

Fig. 1. The experimental unit diagram: *1* – sample cylinder; *2* – measured sample; *3, 4, 5, 12* – valves; *6* – measuring cylinder; *7, 8* – scales; *9, 10* – transparent pipe lines; *11* – water cylinders; *13* – pneumatic pump; *14* – manometer; *15* – relief valve

In the underpressure mode the unit operates as follows. The sample *2* weighted on the weighing balance is placed into the sample cylinder *1* while the valves *3*, *4*, *5*, *12* are opened and the cylinders *1* and *6* have the P_{atm} atmospheric pressure set. After that, the valve *4* is closed and the pneumatic pump *13* is turned on. The pneumatic pump *13* creates in the cylinders *1* and *6* the P_1 underpressure recorded by the manometer *14*. When the desired value of underpressure is reached, the valve *12* is closed as well as further the valves *3* and *5*, and the pressure in the pneumatic pump *13* is equilibrated with the atmospheric pressure through the relief valve *15*. After the valves *3* and *4* are successively opened, due to the underpressure the Δh_1 height of water column in the transparent pipe line *10* changes. This variation is recorded using the scale *8*. Then, the valve *12* is opened and the valve *3* is closed, it results in the atmospheric pressure set again in the measurement system, and the water column returns to its original state. After that, the valve *12* is closed again and the valve *5* is opened, and due to the underpressure the water from the cylinders *11* transfers through the transparent pipe line *10* where the scale *8* shows the variations of the Δh_2. height of water column. These readings are recorded. Then, the valves *3*, *4*, *5*, *12* and the relief valve are opened, and the measurement system returns to its original zero state.

The actions taken have the following theoretical interpretation. In view of the constant temperature of the system, its state in the cylinders *1*, *6* at the P_{atm} atmospheric pressure and after the P_1. vacuum is created may be represented by the equations following the Boyle-Mariotte law:

$$P_1\left(V_c - V_b\right) = P_{atm}\left(V_c - V_b - \Delta V_1\right); \quad (1)$$

$$P_1 V_c = P_{atm}\left(V_c - \Delta V_2\right), \quad (2)$$

where P_{atm} is a numerical value of the atmospheric pressure, kPa; P_1 is a numerical value of the vacuum in the cylinders after air removal, kPa; V_c is the vome of each cylinder, cm³; V_b is the unknown volume of a body, cm³; $\Delta V_1, \Delta V_2$ is the air volume removed from the sample and the measuring cylinders, correspondingly, cm³.

Expressing P_1 from Eqs. (1) and (2) we can obtain respectively:

$$P_1 = \frac{P_{atm}\left(V_c - V_b - \Delta V_1\right)}{\left(V_c - V_b\right)}; \quad (3)$$

$$P_1 = \frac{P_{atm}\left(V_c - \Delta V_2\right)}{V_c}. \quad (4)$$

Making equal the right-hand sides of the Eqs. (3) and (4) and solving for the V_b unknown body volume we obtain:

$$V_b = V_c\left(1 - \frac{\Delta V_1}{\Delta V_2}\right).$$

In the overpressure mode the unit operates as follows. The sample *2* weighted on the weighing balance is placed into the sample cylinder *1* while the valves *3*, *4*, *5*, *12* are opened and the cylinders *1* and *6* have the P_{atm} atmospheric pressure set. After that, the valve *4* is closed and the pneumatic pump *13* is turned on. The pneumatic pump *13* creates in the cylinders *1* and *6* the P_2 overpressure recorded by the manometer *14*. When the desired value of overpressure is reached, the valve *12* is closed as well as the valves *3* and *5* further, and the pressure in the pneumatic pump *13* is equilibrated with the atmospheric pressure through the relief valve *15*. After the valves *3* and *4* are successively opened, due to the overpressure the Δh_1 height of water column in the transparent pipe line *9* changes. This variation is recorded using the scale *7*. Then, the valve *12* is opened and the valve *3* is closed, it results in the atmospheric pressure set again in the measurement system, and the water column returns to its original zero state. After that, the valve *12* is again closed and the valve *5* is opened, and due to the overpressure the water from the cylinders *11* transfers through the transparent pipe line *9* where the scale *7* shows the variations of the Δh_2 height of water column. These readings are recorded. Then, the valves *3*, *4*, *5*, *12* and the relief valve are opened, and the measurement system returns to its original state.

The actions taken have the following theoretical interpretation. In view of the constant temperature of the system, its state in the vessels *1*, *6* at the P_{atm} atmospheric pressure and after the P_2 overpressure is created may be represented by the equations following the Boyle-Mariotte law:

$$P_2\left(V_c - V_b\right) = P_{atm}\left(V_c - V_b + \Delta V_1\right); \quad (6)$$

$$P_2 V_c = P_{atm}\left(V_c + \Delta V_2\right), \tag{7}$$

where P_{atm} is the value of the atmospheric pressure, kPa; P_2 is the value of overpressure in the cylinders, kPa; $\Delta V_1, \Delta V_2$ is the air volume transferred from the atmosphere into the sample and the measuring cylinders, correspondingly, cm³.

Expressing P_{atm} from Eqs. (6) and (7) we obtain:

$$P_2 = \frac{P_{atm}\left(V_c - V_b + \Delta V_1\right)}{\left(V_c - V_b\right)}; \tag{8}$$

$$P_2 = \frac{P_{atm}\left(V_c + \Delta V_2\right)}{V_c}. \tag{9}$$

Making equal the right-hand sides of the Eqs. (8) and (9) and solving for the V_b unknown body volume we obtain an equation for calculating the volume of a measured body:

$$V_b = V_c\left(1 - \frac{\Delta V_1}{\Delta V_2}\right). \tag{10}$$

The density, in its turn, is defined by the following formula:

$$\rho = \frac{m}{V_c\left(1 - \frac{\Delta V_1}{\Delta V_2}\right)}. \tag{11}$$

Application of the Eqs. (5) or (10) requires certain explanations.

In the experimental study we can replace the $\frac{\Delta V_1}{\Delta V_2}$ ratio with the $\frac{\Delta h_1}{\Delta h_2}$ ratio, it can be explained by the following equation:

$$\Delta V = \frac{\pi d^2}{4}\Delta h, \tag{12}$$

where d is the diameter of the transparent pipe line, mm; Δh is the variation of the water column height, mm.

Significantly, at the same value of underpressure (overpressure) the volume of air removed from the cylinders (transferred from the atmosphere into the cylinders) depends on the volume of a measured sample, i.e. with an increase in the volume of a measured sample at $P_1 = \text{const}$ ($P_2 = \text{const}$) the volume of air actually removed from the cylinders (transferred from the atmosphere into the cylinders) decreases. Accordingly, a calibration test of the unit is required. Besides, to simplify further calculations it is better to eliminate the V_c value. Taking into account the Eqs. (12), (5) and (10), this may be represented as follows:

$$\frac{\Delta h_1}{\Delta h_2} = 1 - \frac{V_b}{V_c}. \tag{13}$$

The presented methodology and the developed design can be used to determine the apparent volume and apparent density of not only the sapwood and heartwood parts of the stem wood, but also the bark, roots, branches, and rot.

For the experimental study aimed at measuring the volume and apparent density, we have used wood samples of aspen, spruce, birch, pine, and oak measuring

20×20×10 mm (the latter number shows the along-the-grain size) and taken from the sapwood of tree stems (Fig. 2).

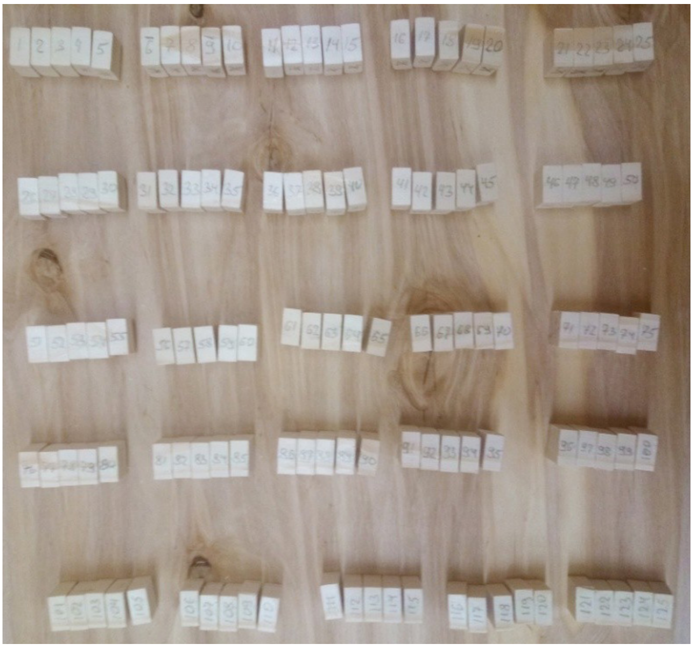

Fig. 2. The wood samples under consideration

125 samples have been selected for each species and taken in the direction from the butt end to the top. The samples have been divided into groups of 5 pieces. The moisture level has been maintained as absolutely dry. We have measured the weight of each sample using the Vibra electronic balance with an accuracy of 0.001 g. The apparent volume of each group has been defined after 10 measurements carried out in the laboratory unit.

Results and Discussion

For the calibration test of the laboratory unit, end blocks of various volumes have been used as a V_b reference body. The pressure values during the calibration test and experiments have been equal to –90, –70, +70 and +90 kPa. As a result, we have obtained the curves (Fig. 3) of the calibration test diagram where the $\frac{\Delta h_1}{\Delta h_2}$ ratio is on the x axis and the V_b volume corresponding to this ratio is on the y axis.

To ease further use, each curve of the calibration test diagram is described by the equation of the following type:

$$y = -kx + b, \tag{14}$$

where y is the volume of the V_b body, cm³; k and b are the equation coefficients obtained from the calibration test results, and x is the $\frac{\Delta h_1}{\Delta h_2}$ ratio.

It is evident from the Eq. (14) that the first point of the calibration curves should have the [1; 0] coordinates, i.e. when $V_b = 0$, and the ratio $\frac{\Delta h_1}{\Delta h_2} = 1$. Other points are determined by the coordinates depending on the volume of the reference bodies and the $\frac{\Delta h_1}{\Delta h_2}$ ratios corresponding to them. Except the equations, the curves also represent the approximation validity coefficients. The value $R^2 = 1$ indicates an unambiguous correlation between the V_b and $\frac{\Delta h_1}{\Delta h_2}$ values as well as the high confidence of the experiment results.

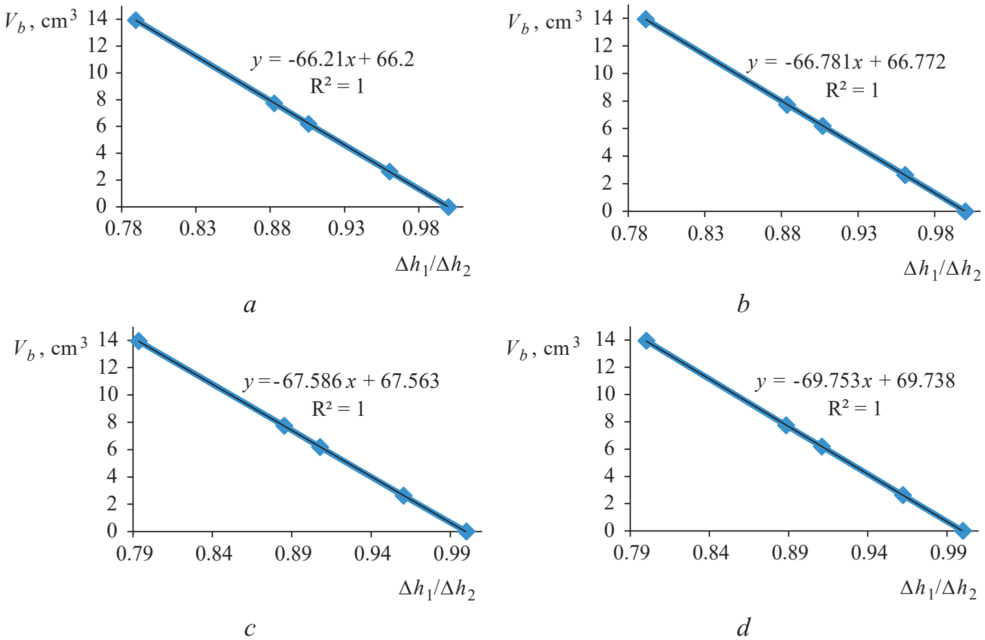

Fig. 3. The calibration curves at: *a* – –90 kPa; *b* – –70 kPa; *c* – +70 kPa; *d* – +90 kPa

The experimental data on the apparent density of the wood samples of various species which have been obtained in the conditions of different measurement modes are represented in fig. 4.

The obtained experimental data show that the apparent density values measured in the underpressure mode vary within the ranges of 1.361 to 1.434 g/cm³ for aspen, 1.151 to 1.348 g/cm³ for spruce, 1.356 to 1.402 g/cm³ for birch, 1.298 to 1.444 g/cm³ for pine, and 0.99 to 1.147 g/cm³ for oak. The respective apparent density values measured in the overpressure mode are within 1.316 to 1.372 g/cm³ for aspen, 1.106 to 1.274 g/cm³ for spruce, 1.292 to 1.356 g/cm³ for birch, 1.285 to 1.412 g/cm³ for pine, and 0.904 to 1.138 g/cm³ for oak. According to the available information [25] it is known that the cell-wall density determination by the pycnometry method applied for oak and other ring-porous and diffuse-porous species is difficult and gives unreliable results. The obtained experimental data on the oak apparent density have confirmed it.

The curves clearly show the difference between the results obtained in different operational modes of the measurement system. In all the cases, the density measured in the underpressure mode is greater than that measured in the overpressure mode and reaches the values up to 1.444 g/cm³. This value may confidently be considered true as it insignificantly differs from the value of cell-wall density 1.46 g/cm³ measured by the helium pycnometry method.

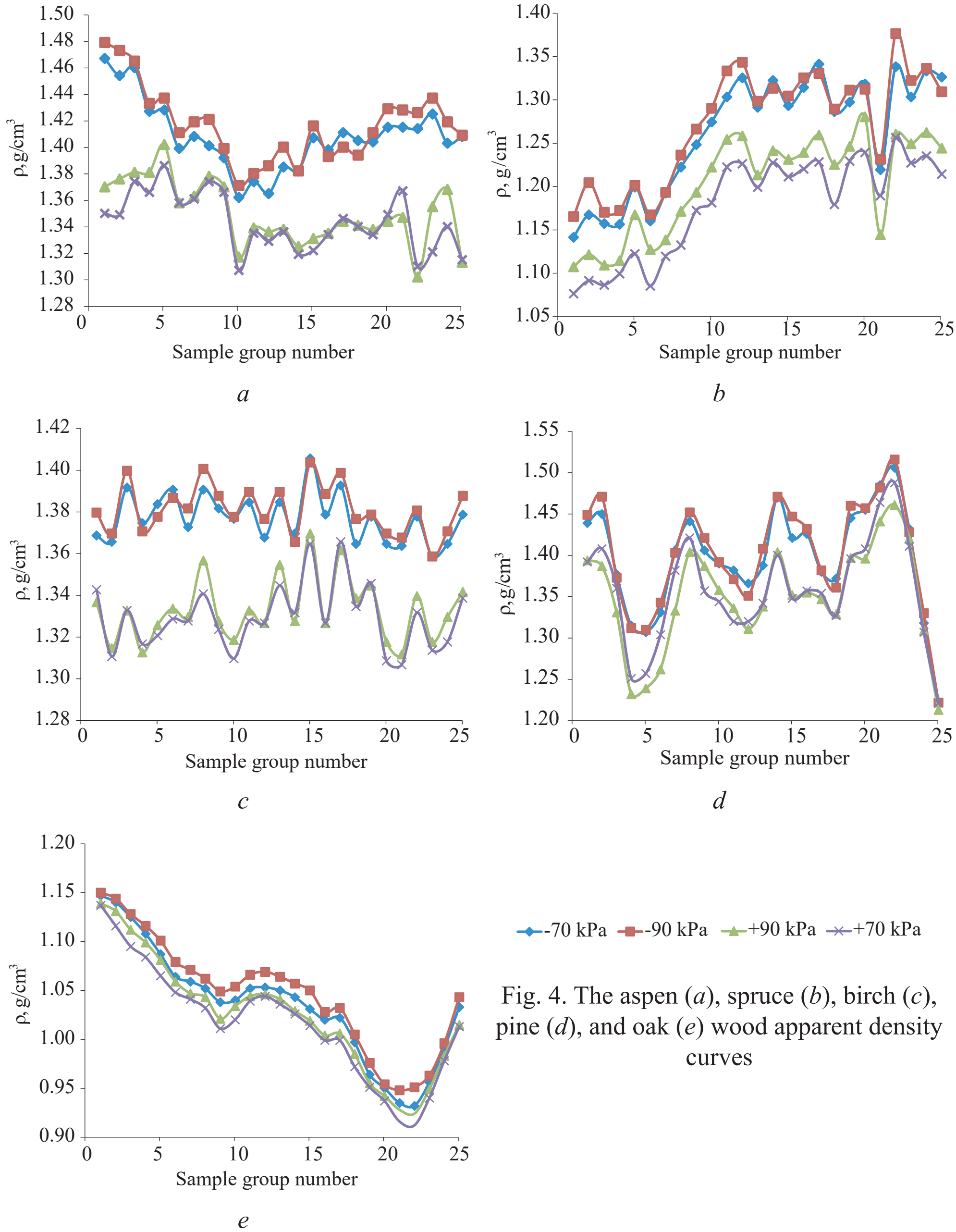

Fig. 4. The aspen (*a*), spruce (*b*), birch (*c*), pine (*d*), and oak (*e*) wood apparent density curves

Conclusions

The literature review has shown 4 main methods of measuring the cell-wall density of wood and porous materials: 3 of them are classified as direct methods (suspension, mercury porosimetry, and pycnometry) and 1 is indirect (optical (planimetric) method).

At the present time, the most common method is helium pycnometry. With regard to all the advantages and disadvantages of this method, the developments of new methods for determining the cell-wall density of wood and porous materials are carried on.

An alternative, authors' method for measuring the volume and determining the apparent density of wood and porous materials in the atmospheric air has been proposed. This method is theoretically justified and does not contradict the basic principles and laws of thermodynamics.

The efficiency of the proposed method and the high reliability of the obtained results have been proven experimentally.

With the use of the developed experimental unit, the volumes and apparent density values of various species of wood have been measured in different operational modes of the measurement system.

The lowest values of the apparent density have been obtained in the conditions of overpressure, and the highest ones – in the conditions of underpressure. It is related to the differences in the thermodynamical processes of air compression and rarefaction. The properties of thin air when compared with the compressed one are more similar to those of an ideal gas. Also, it is crucial how deeply air penetrates into the pores of samples during the compression and rarefaction processes. The result deviations between the highest and lowest values of the apparent density measured in different modes are, respectively, the following: for aspen – 6.83 %, for spruce – 8.54 %, for birch – 6.35 %, for pine – 6.82 %, and for oak – 3.91 %. The greatest deviation between the highest values of apparent density and the conventional value of 1.46 g/cm^3 are respectively the following: for aspen – 1.78 %, for spruce – 7.67 %, for birch – 3.97 %, for pine – 1.1 %, and for oak – 21.44 %.

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