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Orginal Article



# The impact of density, temperature, moisture, and test direction on the thermal conductivity coefficient in pine wood

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**Abstract:** The article focuses on the study of the thermal properties of pine wood, a material traditionally used in construction, especially in Poland. The trend towards sustainable construction necessitates a deeper analysis of its properties. Due to the insufficient amount of data in the literature on the thermal conductivity of pine wood, detailed studies were conducted, taking into account different wood densities. Seasoned wood samples were subjected to various processes and tests, measuring the heat conduction coefficient under different conditions. These results are relevant in the context of sustainable construction and will assist in further research on wood as a building material. The studies also took into account the effects of temperature and humidity on the thermal properties of wood, which are crucial for its application in various environmental conditions.

**Keywords:** wood, thermal conductivity coefficient λ for wood, thermal insulation of wood

## 1. Introduction

Wood, one of the oldest materials used in construction, has fascinated and intrigued researchers with its unique properties since ancient times. Its durability means that for centuries, it has served humanity as a fundamental construction material, unmatched in many respects. However, with the development of civilization, the emergence of new materials, and an increasing emphasis on sustainable, ecological solutions in construction, the properties of wood began to be subjected to even deeper analysis.

Modern society, increasingly aware of the impact of human activity on the environment, strives to create energy-efficient buildings that minimize energy consumption not only during their construction but also throughout their life cycle. In this context, the thermal insulation properties of wood become not only important but crucial for the future of sustainable construction.

Wood, as a traditional building material, is intensively studied for its insulating properties, especially in the context of modern aspirations for ecological and energy-efficient construction. Contemporary research focuses on various thermal characteristics of wood, such as specific heat or thermal diffusion, and on different modification technologies and combinations with other materials that can improve or change its properties. The results of these studies emphasize the importance of factors such as humidity and temperature for the thermal properties of wood-based materials. Moreover, there are many innovative approaches, such as the addition of nanofibers or graphene impregnation, which open up new perspectives for the application of wood in various fields of construction and industry.

Research on the thermal properties of wood, such as specific heat, thermal conductivity, and thermal diffusion, allows for a better understanding of heat conduction processes in wood [1]. Studies on beech and fir wood confirm its ability to accumulate energy and provide thermal insulation [1]. Meanwhile, the introduction of cellulose nanofibers (CNF) to polyurethane foam (PUF) significantly improves its insulating properties, which is significant in construction [2].

Experiments conducted on oak, beech, and spruce wood indicate their orthotropic thermal conductivity properties, allowing the modeling of heat conduction in different directions [3]. The technology of impregnating poplar veneer with graphene and polyvinyl alcohol leads to a significant increase in thermal conductivity, which may find application in various industrial sectors [4].

Using wood waste and expanded polystyrene in the production of composites can lead to the creation of materials with adequate thermal insulation, which is important in construction [5]. Studies on various wood-based materials indicate the dependence of their insulating properties on humidity content and temperature [6]. The use of wood waste in the production of insulation foam shows potential in terms of the energy efficiency of buildings [7]. Meanwhile, impregnation of beech wood with a silver nanosuspension before its thermal modification leads to significant changes in its physical and mechanical properties [8]. Finally, multiscale modeling of wood's thermal conductivity is crucial for analyzing the thermal performance of laminated wood [9].

Research on the impact of humidity on the thermal properties of a wood-concrete composite shows that adding wood chips to the sand-cement mixture increases thermal insulation ability by reducing thermal conductivity and diffusion, but these properties strongly depend on water content [10]. In studies on wooden aerogel with straightened cellulose fibers, it has been shown that it has very low density and ultra-low thermal conductivity, making it a promising insulation material [11]. An analysis of the influence of air humidity and temperature on the thermal conductivity of wood-based materials emphasizes the importance of these factors for thermal properties [12].

The use of sepiolite in the construction of wood strand lumber (OSL) leads to a significant increase in thermal conductivity, improving panel hardness due to more effective resin curing [13]. Research on the influence of humidity and temperature on the thermal conductivity coefficient ($\lambda$) of insulating materials used inside buildings emphasizes the need to understand the influence of these factors on insulation performance [14]. The book "Handbook of Wood Chemistry and Wood Composites" analyzes the chemical modification technologies of wood in the context of durability and sustainable development [15].

Studies on the effectiveness of the thermal conductivity of compressed wood suggest that its values increase proportionally with density growth [16]. A study on the thermal conductivity of cork insulation board emphasizes the standard values of this coefficient for this material [17]. Finally, an analysis of laminated wood using a computer homogenization model indicates an accurate prediction of the mechanical properties of wood [18].

This article aims to introduce the topic of heat conduction in wood. Conducting research allowed determining the values of the heat conduction coefficient for different densities of pine wood, the most commonly used species in construction in Poland. The first part of the study describes the research position and the method of sample preparation. The second part presents the obtained results.

The main goal of the research was to determine the relationship between the heat conduction coefficient and the density of pine wood. The study includes a description of sample preparation, research position, and presents the obtained results. The results encompass values of the heat conduction coefficient in different temperature ranges of the study and at different humidities.

The conclusion of the article emphasizes the importance of a detailed understanding of the thermal properties of wood, which has a significant impact on its use in construction, especially in the context of energy-efficient and sustainable construction. The obtained results confirm the high potential of wood as a material with excellent thermal insulation properties.

The final remarks of the article stress the significance of comprehending the thermal attributes of wood for its application in the construction sector, particularly concerning eco-friendly and energy-efficient building. The derived data corroborates wood's noteworthy potential as a material possessing superb thermal insulation characteristics.

## 2. Laboratory station

The thermal conductivity coefficient measurement was conducted using the LaserComp instrument, designed in accordance with ASTM C518-91 "Standard Test Method for Steady-State Heat Flux Measurements and Thermal Transmission Properties by Means of the Heat Flow Meter Apparatus." The LaserComp FOX 314 instrument consists of a base with a display and a keyboard, as well as a tightly sealed measurement chamber [19]. The measurement chamber accommodates the sample placed between a permanently mounted upper plate and a movable lower plate. Both plates are equipped with a cooling and heating system, comprising thermoelectric elements (Peltier elements), independently controlled for the central and outer parts of the plates. Plate temperatures are independent and can be maintained within a range from -20 to 95°C with an accuracy of 0.02°C. Before commencing the experiments, the instrument underwent calibration to ensure measurement accuracy. The instrument operates based on the steady-state heat flux method, involving the flow of a constant heat flux through a sample at a specified temperature. The Lambda coefficient is determined based on the density of the heat flux and the temperature difference on both sides of the sample.

## 3. Laboratory samples

The samples intended for the research were sourced from naturally seasoned wood. After being cut to the appropriate dimensions and planned to achieve a smooth surface, they were placed in a dryer at a temperature of 60°C until a constant mass was reached. The drying process caused the samples to warp, necessitating planning to regain parallel surfaces. Rectangular samples were measured and weighed to determine the density of each. The initial determination of the thermal conductivity coefficient for the samples in an air-dry state was conducted at a temperature of 12.5°C (lower plate L=0°C and upper plate U=25°C). Subsequent tests were carried out at temperatures of 22.5°C (lower plate L=10°C and upper plate U=35°C), 32.5°C (lower plate L=20°C and upper plate U=45°C), and 42.5°C (lower plate L=30°C and upper plate U=55°C).

The next stage of the research involved investigating the thermal conductivity coefficient under laboratory conditions. Therefore, the samples previously tested in an air-dry state were placed in the laboratory for approximately one month at a temperature of 25°C and a humidity of 45%. During this period, they were periodically weighed until a constant mass was achieved. After confirming the surface parallelism, the tests were conducted at a temperature of 22.5°C (lower plate L=10°C and upper plate U=35°C).

Following the completion of the laboratory conditions testing, the samples were placed in a climatic chamber at a temperature of 25°C and a humidity of 75%. During the time the samples were in the climatic chamber, they were periodically weighed until a constant mass was obtained.

After completing the tests across the fibers, the samples were cut into 2.5 cm slices, rotated, and glued together to conduct tests along the fibers. The results are presented below. The tests were conducted for wood under laboratory conditions at a temperature of 22.5°C.

Fig. 1. Cross-section along the fibers of the sample

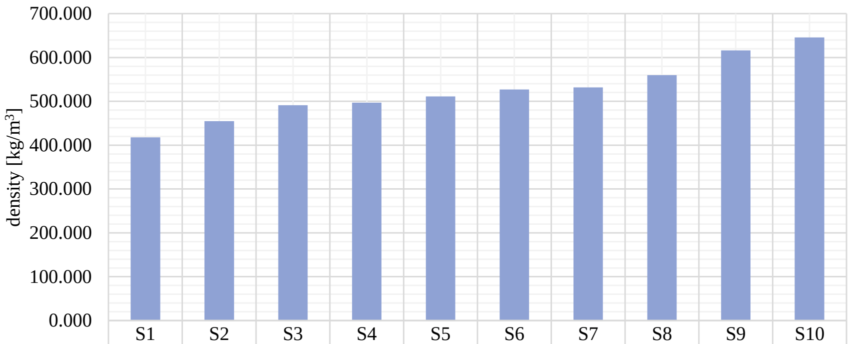
Fig. 2. Cross-section along the fibers of the sample


Fig. 3. Cross-section across the fibers of the sample


Fig. 4. Cross-section across the fibers of the sample

The samples exhibited varying volumetric density. Density was determined by dividing the weight of the sample in an air-dry state by its volume. The measurement results for density are provided below.

Table. 1. Volumetric density of samples S1 to S10



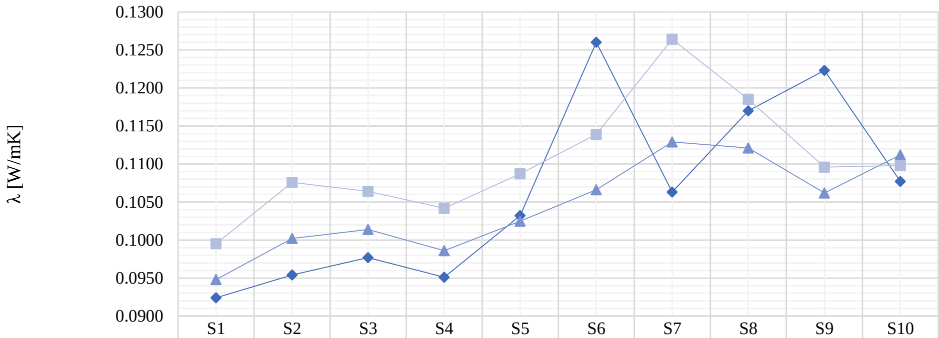

| | S1 | S2 | S3 | S4 | S5 | S6 | S7 | S8 | S9 | S10 |
|---|---|---|---|---|---|---|---|---|---|---|
| density | 418 | 455 | 491 | 497 | 511 | 527 | 532 | 560 | 616 | 646 |

## 4. Research results

Below are the results of various tests conducted on the same samples. Thermal conductivity coefficient measurements were conducted for pine wood samples (S1 to S10) with respect to sample moisture content, test temperature, and the orientation of fibers within the sample.

Thermal conductivity coefficient measurements were conducted for the wood samples, varying based on the temperature and moisture content during the seasoning of the samples. The samples were stored at a temperature of 25 degrees Celsius with humidity for air-dry conditions, 45% humidity for laboratory conditions, and 75% humidity for the climatic chamber conditions. The research results are presented in the table below.

Table. 2. Thermal Conductivity Coefficient ($\lambda$) value as a function of moisture content in the tested wood

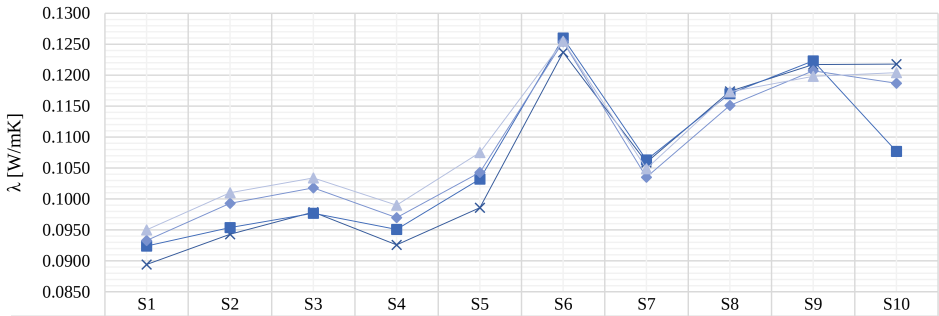



| | S1 | S2 | S3 | S4 | S5 | S6 | S7 | S8 | S9 | S10 |
|---|---|---|---|---|---|---|---|---|---|---|
| air-dry | 0.0924 | 0.0954 | 0.0977 | 0.0951 | 0.1032 | 0.126 | 0.1063 | 0.117 | 0.1223 | 0.1077 |
| laboratory | 0.0948 | 0.1002 | 0.1014 | 0.0986 | 0.1025 | 0.1066 | 0.1129 | 0.1121 | 0.1062 | 0.1112 |
| climate chamber | 0.0995 | 0.1076 | 0.1064 | 0.1042 | 0.1087 | 0.1139 | 0.1264 | 0.1185 | 0.1096 | 0.1098 |

The research was conducted at different temperatures, taking into account both the upper plate (U) and lower plate (L) temperatures, from which the average test temperature (temp) in degrees Celsius was calculated. The parameters for each test are as follows:

- for L1=0°C and U1=25°C, the test temperature was 12.5°C,
- for L2=10°C and U2=35°C, the test temperature was 22.5°C,
- for L1=20°C and U1=45°C, the test temperature was 32.5°C,
- for L2=30°C and U2=55°C, the test temperature was 42.5°C.

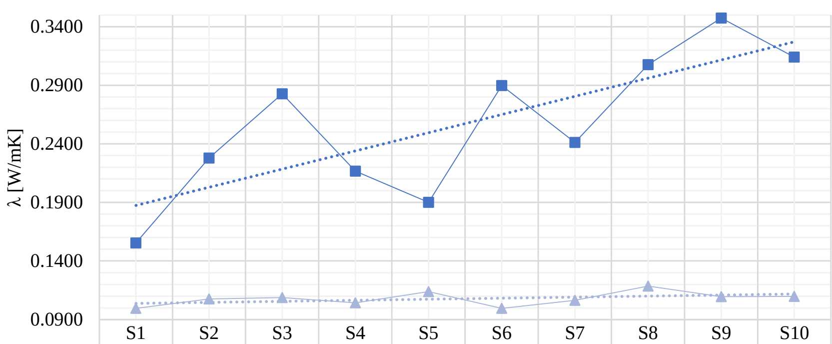
Table. 3. Thermal Conductivity Coefficient (λ) value as a function of test temperature




| | S1 | S2 | S3 | S4 | S5 | S6 | S7 | S8 | S9 | S10 |
|---|---|---|---|---|---|---|---|---|---|---|
| 12.5C | 0.0894 | 0.0943 | 0.0979 | 0.0926 | 0.0986 | 0.1237 | 0.1059 | 0.1174 | 0.1217 | 0.1218 |
| 22.5C | 0.0924 | 0.0954 | 0.0977 | 0.0951 | 0.1032 | 0.1260 | 0.1063 | 0.1170 | 0.1223 | 0.1077 |
| 32.5C | 0.0933 | 0.0993 | 0.1018 | 0.0970 | 0.1043 | 0.1254 | 0.1035 | 0.1151 | 0.1207 | 0.1187 |
| 42.5C | 0.0950 | 0.1010 | 0.1034 | 0.0990 | 0.1075 | 0.1255 | 0.1049 | 0.1173 | 0.1198 | 0.1204 |

The samples were analyzed in two different orientations: along the direction of the fibers and perpendicular to them. To ensure uniformity and precision in the tests, all samples were pre-dried until they reached a constant mass, eliminating the influence of moisture on the obtained results. The experiments were conducted under controlled temperature conditions. It was determined that the overall ambient temperature during the tests was 22.5°C. Additionally, the lower test plate had a temperature of 10°C, while the upper one reached a temperature of 35°C. The results obtained from the tests, both for samples along the fibers and across them, were compiled and presented in the table below.

Table. 4. Thermal Conductivity Coefficient (λ) value as a function of testing direction




| | S1 | S2 | S3 | S4 | S5 | S6 | S7 | S8 | S9 | S10 |
|---|---|---|---|---|---|---|---|---|---|---|
| along the grain | 0.1554 | 0.2278 | 0.2828 | 0.2167 | 0.19 | 0.2899 | 0.2412 | 0.3076 | 0.3475 | 0.3141 |
| across the grain | 0.0995 | 0.1076 | 0.1087 | 0.1042 | 0.1139 | 0.0995 | 0.1064 | 0.1185 | 0.1096 | 0.1098 |

## 5. Research analysis

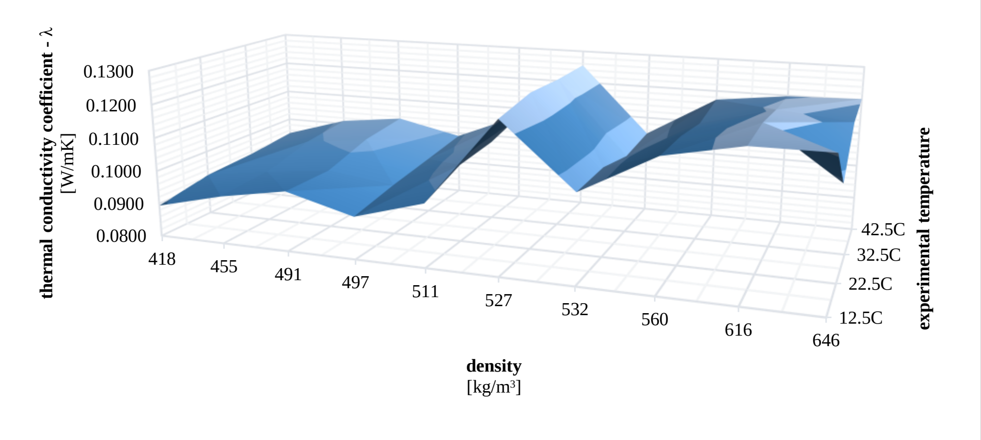
The study of the thermal conductivity coefficient (λ) expressed in W/m·K for wood samples from S1 to S10 provided valuable information regarding the thermal properties of wood concerning density, moisture content, and temperature. Concerning density, samples with lower density, such as S1 and S2, exhibited lower λ values (e.g., 0.0924 W/m·K for S1 in air-dry conditions) compared to samples with higher density, like S9 and S10.

Another observed dependency was related to the influence of moisture on thermal conductivity. As humidity increased from air-dry conditions to a climatic chamber with 75% humidity, the λ value for sample S1 increased from 0.0924 W/m·K to 0.0995 W/m·K, suggesting that moister wood samples have better conducting properties, likely due to the superior thermal conductivity of water compared to air.

An analysis of temperature variability revealed trends for most samples. For sample S1, λ values at different temperatures fluctuated between 0.0894 W/m·K and 0.0950 W/m·K, indicating an increase in thermal conductivity with rising test temperature. However, some samples, such as S6, exhibited non-linear behavior. In the case of S6, the λ value increased from 0.1237 W/m·K to 0.1260 W/m·K for the initial two temperatures but then decreased to values of 0.1254 W/m·K and 0.1255 W/m·K at higher temperatures, suggesting potential non-linearities in the thermal conductivity of certain wood samples.

Finally, the testing direction revealed differences in λ values. For sample S1, the λ value in the direction along the fibers was 0.1554 W/m·K, significantly differing from the value of 0.0995 W/m·K in the direction across the fibers. A similar trend was observed for other samples, emphasizing the impact of the structural anisotropy of wood on its conducting properties. In engineering and design applications, this anisotropy of wood's thermal conductivity should be considered to ensure optimal material utilization.

Table. 5. Chart depicting the relationship between λ values, density, and test temperature




## 6. Conclusions

The analysis of the thermal conductivity capabilities of various material samples, labeled as S1 to S10, provides insight into the complex relationships between their density, temperature, and the direction of heat conduction. In light of the presented data, several key observations stand out:

1. A nonlinear influence of the increase in wood density on the rise in the thermal conductivity coefficient has been observed.
2. Analysis of the results for samples with the lowest and highest densities revealed that an approximate 45% increase in density corresponds to about a 22% increase in the thermal conductivity coefficient value.
3. A nonlinear nature of the temperature's impact on the increase in the lambda coefficient value was identified. For the samples with lower densities, the increments in the lambda coefficient values with rising temperature were significantly higher than for those with higher densities.
4. Studies of the same samples along and across the grain have demonstrated significant differences in the character of the increase in the lambda coefficient value. For low-density materials, the differences are at the level of several dozen percent; at high densities, the lambda coefficient value when measured along the fibers can be up to three times greater.

The conclusions drawn from this study are of paramount importance for engineering and design applications related to wood. Understanding the impact of various factors on the thermal conductivity of wood can lead to better design and utilization of wood in various applications, especially in the context of thermal insulation and construction.

Although many samples exhibit clear trends concerning the analyzed parameters, the nonlinear behavior of some samples under specific conditions suggests the need for further in-depth research to better understand the mechanisms of thermal conductivity in wood.

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