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# Measurements of the dependence of wood's permeability to air on the temperature of the pyrolysis

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## Abstract

The paper deals with the wood's (in this case pine) longitudinal permeability to air and its possible dependence on the temperature of the pyrolysis. The measurement of permeability was indirect and conducted on the original stand constructed solely for this purpose. Before every measurement a special sample preparation procedure was conducted for each sample group. Every group of samples was preheated up to the temperature previously set in the oxygen-less environment. After that, samples were cooled down to the room temperature. The following parameters were measured directly: sample length and diameter, pressure difference, and time. After numerous measurements of the mentioned values, the permeability of wood to air was calculated using the Darcy's law for a given pyrolysis temperature. The results show a distinct dependence between the wood's permeability to air and the pyrolysis temperature. The minimum value of the permeability is on the level of 0.56 D for temperature of 50 °C and is growing up to the value of 5.8 D (over ten times of the initial value) for the temperature of 350 °C.

# 1  Introduction

The permeability of wood to air turns out to be very important physical property when the wood is considered as a fuel for the combustion process. It decides how well (and how fast) does the wood dry and how well does the air mix with a packed bed of wood inside a combustion chamber of any sort.

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The air always flows into the fuel bed with some level of exceed in order to ensure that the combustion process is complete. Knowing the exact relationship between the permeability of wood and the pyrolysis temperature could enable a better understanding of the combustion process and setting the proper air exceed coefficient for a given type of the wood. The wood permeability is also a key issue when the wood is treated chemically. All of the above, it could contribute to improving the combustion efficiency.

Tanaka *et al.* measured permeability to air for sugi (Cryptomeria japonica) wood in the three directions: radial, longitudal and tangential (Fig. 1). These results indicate that sugi is one of the least transversally permeable softwoods, with the permeability equal to $10^{-13}$ m$^2$ (0.1D, 1D= 0.99 $\times$ $10^{-12}$ m$^2$), which could contribute to the difficulties encountered in the drying and chemical treatment of sugi [1]. ]
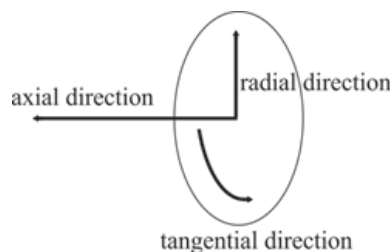


Figure 1: Various possible directions of fluid flow inside the wood.

Jinman *et al.* showed that the permeability of Pinus koraiensis and Larix dahurica in radial direction is greater than in tangential and the permeability of Populus davidiana Dode and Betula platyprhylla Suk in tangential direction is greater than in radial. The results of the experiment showed that the variation of wood permeability (in function of the direction) is larger than those of other physical properties, because wood has complex capillary structure [2].

Redman *et al.* highlighted the dramatic anisotropy ratios and the vast difference between various Australian hardwood species. For some of them, the longitudinal to transverse anisotropy ratio was in the order of $10^6$ (Eucalyptus pilularis, Eucalyptus marginata). No permeability values were measured for spotted gum (Eucalyptus maculata) in the radial direction as, even after 24 hours, no noticeable measurement could be made by the authors. This indicated, that this species is highly impermeable in this direction (permeability of value less than $10^{-23}$ m$^2$) [3].

The permeability to air, as an important physical property of the wood,

has been measured for many various species of the wood so far. However, the dependence of the permeability in function of the pyrolysis temperature is still not quite well investigated.

## 2    Measurements of wood permeability to air

The measurements of air permeability for wood (pine) were performed on an original stand manufactured solely for this purpose. The process consisted of preparing wood cylinders and then heating them up to the set temperature (from $50\,^\circ$C to $350\,^\circ$C) in a stove and secondly cooling them down to the room temperature in order to place inside the steel sleeve. The pine cylinders were fixed to the sleeve by the epoxide resin, the sleeve itself was then inserted inside the steel cylindrical container. The methodology based on blowing the air under pressure into the container and measuring its velocity after crossing the wood cylinder.

## 3    Test stand

The test stand consisted of the following devices: air compressor, differential pressure converter, steel container equipped with interchangeable steel sleeve (containing the biomass) and the bubble velocity meter (Fig. 2). The upper part of the container is screwed and can be dismantled in order to place the interchangeable steel sleeve (with smaller diameter) inside the container (bigger diameter), between two circular seals. Such construction allows replacing biomass samples in a quick and easy way.

## 4    Preparing the samples

At the beginning of the process, each sample had cylindrical shape with 16 mm diameter and approximately 60 mm in height. Next, a group of 3 samples was inserted into the stove and heated up to the given temperature with the oxygen-less atmosphere, different for every group (from $50\,^\circ$C up to the $350\,^\circ$C, every $50\,^\circ$C). Then the samples were removed from the stove in order to naturally cooled down to the room temperature. Every sample was inserted into steel sleeve (Fig. 3) and fixed to it with epoxide resin (the samples were covered with varnish beforehand in order to prevent the epoxide resin from percolating into the wood). Dimensions of the samples were different as a result of pyrolytic decomposition of the wood – in the

next step, with the use of milling machine, each sample was leveled out and shortened so that every measurement was conducted on a biomass cylinder with the same height of 30 mm. Different diameters were taken into consideration in the calculations.
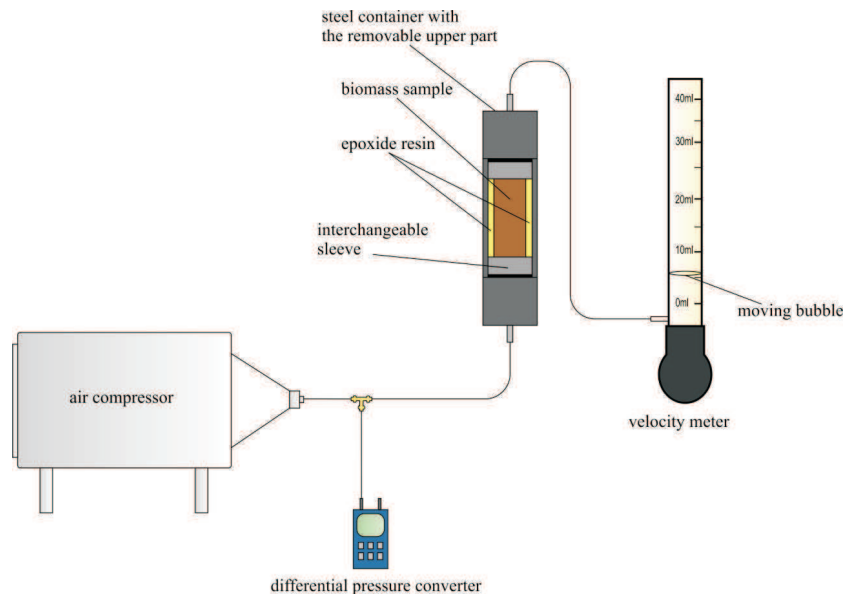


Figure 2: The test stand.



Figure 3: Interchangeable steel sleeve with biomass (pine) samples for permeability measurements.

# 5 Methodology

The measurement of the wood (pine) permeability to air was indirect. It was calculated from the simple Darcy's law

$$u = -\frac{K}{\mu}\frac{\Delta P}{l}\,,\qquad(1)$$

after appropriate transformations:

$$K = -\frac{u\mu l}{\Delta P}\,,\qquad(2)$$

where: $\Delta P$ – pressure difference, $K$ – permeability, $\mu$ – dynamic viscosity of the fluid (air), $l$ – length (cylinder height), $u$ – velocity of the air flowing through porous media (wood).

In order to determine the permeability, measurements of the velocity of the air, length of the wood sample and the pressure difference between the compressed air and the atmosphere were required.

The pressure difference was measured during the flow of the compressed air by the differential pressure converter (Fig. 2). The air could not flow through epoxide resin in the sleeve so it was forced to flow through cylindrical porous biomass media of the given diameter. The velocity of the flow through wood could not have been measured directly, thus it was calculated basing on the continuity law

$$A_1 u = A_2 u_x\,,\qquad(3)$$

where:$A_1$ – cross section area of the sample, $u$ – velocity of air flowing through sample, $A_2$ – cross section area of the bubble velocity meter, $u_x$ – velocity of air in the bubble velocity meter. After some transformations, Eq. 3 allows to calculate the velocity of air in the sample by measuring the time in which a bubble passes through a given volume:

$$u = \frac{A_2 u_x}{A_1}\,,\qquad(4)$$

$$u = \frac{1}{A_1}\frac{V_2}{t}\,,\qquad(5)$$

where: $V_2$ – volume of the test section of the bubble velocity meter (constant and equal to 40 ml, Fig. 2), $t$ – time needed for the bubble to pass through test section.

As mentioned before, length of every sample was set to 30 mm. The dynamic viscosity of air was constant and equal to $17.08{\times}10^{-6}$ Pa s.

For the samples prepared in different temperatures, different pressure values caused different bubble velocities. Thus, for every measurement the pressure value was set independently in order to obtain a measurable bubble velocity. For every group of samples a large amount of measurements (200–300) was conducted so that the mean values of the permeability for each group (i.e., for each pyrolysis temperature) was statistically significant.

# 6 The results

The permeability measurements were performed for samples obtained at different pyrolysis temperatures (from 22 °C up to the 350 °C). The measurement itself was conducted at room temperature. Nevertheless, the pyrolysis caused irreversible changes in the wood's structure and even after cooling wood down to the room temperature, the permeability to air will be different than before pyrolysis, as shown in Fig. 4.

The dependence of the wood permeability from the pyrolysis temperature is complex as shown in Fig. 4. In the range of temperatures from 50 °C to 150 °C the permeability is smaller than for the wood at room temperature (not heated up at all). One of the possible explanations of this phenomena is that the wood's resin blocks the pores in that range of temperatures thus making it difficult for air to pass through it. The inner structure of pine wood contains many long resin conduits along the trunk and branches, which are also connected with transverse conduits. The main component of the resin is a class of naturally occurring organic chemicals called terpenoids. The melting point of these substances occurs in a range of temperatures from 100 °C to 130 °C while the vaporization temperatures are also diversified: from 156 °C to 224 °C [4]. These values may suggest that in the range of temperatures from 50 °C to 150 °C the resin movement caused by the heating process has led to blocking the pores, and when the wood was cooled down to the room temperature – the pores have remained blocked (thus the decrease in permeability is being observed).

In the range of temperatures from 200 °C to 350 °C a large increase (up
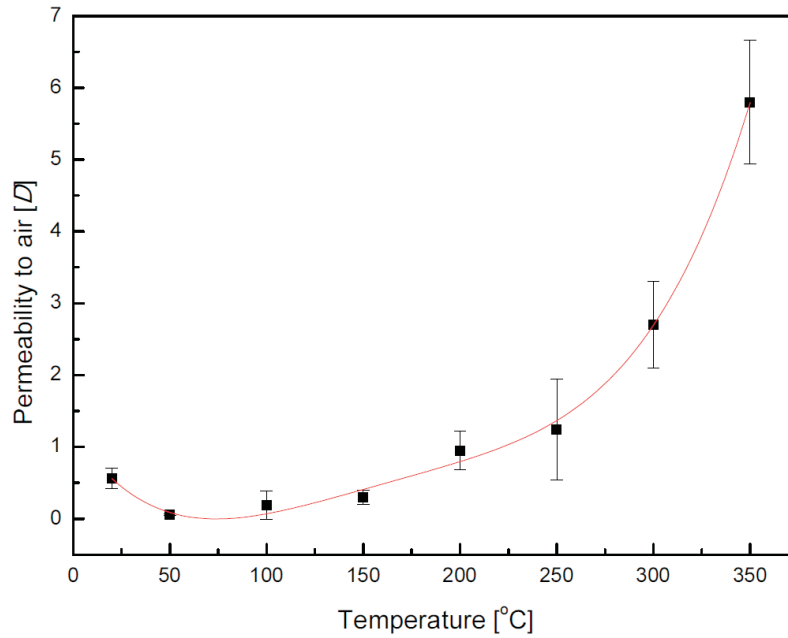
Figure 4: Permeability of biomass (pine wood) to air as a function of pyrolysis temperature (measurement was performed at room temperature). 1D (Darcy) $= 0.99 \times 10^{-12} \mathrm{m}^2$.

to ten times initial value) in permeability is observed. It is caused by the decrease in density of the wood and by an increased size of the pores as a result of devolatilization of wood's volatiles. Since the resin components start to evaporate at $156\,^\circ\mathrm{C}$, this may also contribute to an increase in permeability.

The curve in Fig. 4 shows an approximate plot of the wood's permeability to air as function of pyrolysis temperature. It can be expressed as the following formula

$$2.9 \cdot 10^{-9} T^4 - 1.9 \cdot 10^{-6} T^3 + 4.5 \cdot 10^{-4} T^2 - 0.004 T + 1.2\,[D]\,, \qquad (6)$$

where: $T$ – the temperature the wood was heated up to [K].

# 7  Conclusions

The pine wood permeability to air, in function of the pyrolysis temperature was investigated. a strong dependence between the permeability and the

pyrolysis has been reveled. For the lower temperatures the permeability decreases (compared to the room temperature), but for higher temperatures the permeability reaches values up to 12 times the value for the room temperature.

This phenomena is strongly linked to the fact that the wood's inner structure changes when treated with high temperatures as a result of the devolatilization and deformation of the inner structure. Even after cool down to the room temperature, the changes in the structure are so significant, that the properties such as the permeability to air are irreversibly changed.

An empirical formula for calculating the permeability of pine wood in the function of the pyrolysis temperature was determined.

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