ONLINE ISSN 2069-7430
ISSN-L 1841-4737
PRO LIGNO
www.proligno.ro
Vol. 11 N° 2 2015
pp. 31-38

# INFLUENCE OF MOISTURE DIFFUSION RATE OF BOUND WATER UPON THE DRYING TIME OF STEAMED AND UNSTEAMED BEECH WOOD

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***Abstract***

*The paper aims at establishing the drying time of beech wood below fiber saturation point, by taking into consideration the influence of thickness, drying temperature, pre-treatment by steaming and wood type (white wood compared to red heart). In order to achieve relevant results, an experimental study concerning the water vapor transmission rate of bound water in steamed and unsteamed beech wood samples, containing either only white wood or only red heart, was performed. Based on these results, the diffusion coefficients, the drying speed and the drying time were established for each wood grade. Important findings regarding the influence of drying time and wood type were reported.*

**Key words**: *beech wood; moisture diffusion; water vapor transmission; drying time; drying speed; steamed beech; red heart wood.*

## INTRODUCTION

The drying of wood at moisture contents below fiber saturation point is slower than in the range of high moisture contents (green wood). This is due to the fact that, in this stage of drying, only bound water is still present in wood, located in the cell walls and bound to the wooden substance by very strong forces. The movement of bound water inside wood, from the inner layers towards the surface, is called diffusion.

In steady-state diffusion, the moisture diffusion rate ($J$) is proportional to the gradient in moisture concentration according to Fick's first law of diffusion. Because the moisture concentration is almost directly proportional to the moisture content gradient (Nelson 1986), the moisture diffusion rate of bound water in wood can be written as:

$$J = -\rho_0 \cdot D \cdot \frac{\partial u}{\partial x} \quad [\mathrm{kg/m^2s}] \qquad (1)$$

where:

$D$ is the moisture diffusion coefficient, in $m^2/s$;

$\rho_0$ -oven-dry density of wood, in $kg/m^3$;

$\frac{\partial u}{\partial x}$ - moisture content gradient over the distance $x$ (measured in flow direction), in 1/m.

In case of bound water, mostly present in wood in vapor form, one can assume that the diffusion rate ($J$) is nearly equal to the water vapor transmission rate ($WVTR$), which can be determined experimentally according to ASTM E86:80, by measuring the moisture quantity ($\Delta M$) that passes through the cross section ($A$) of a wood sample in a certain time interval ($\Delta t$):

$$WVTR = \frac{\Delta M}{\Delta t} \cdot \frac{1}{A} \quad [\mathrm{kg/m^2s}] \qquad (2)$$

Assuming that,

$$WVTR \cong J \qquad (3)$$

the moisture diffusion coefficient ($D$) can be deducted from Eq. (1), as:

$$D = \frac{WVTR}{\rho_0 \cdot \frac{\Delta u}{\Delta x}} \quad [\mathrm{m^2/s}] \qquad (4)$$

where:
*WVTR* is the water vapor transmission rate, in kg/m$^2$s, experimentally determined;
$\rho_0$ - oven-dry density of wood, in kg/m$^3$;
$\frac{\Delta u}{\Delta x}$ - moisture content gradient over the distance over which the flow took place, measured in flow direction, in 1/m.

By means of the moisture diffusion coefficient, the drying speed *w* (expressed in %/h) can be computed, by means of Eq. (5):

$$w = \frac{D \cdot \frac{\Delta u}{\Delta x}}{s} \cdot 3{,}6 \cdot 10^5 \quad [\%/\mathrm{h}] \qquad (5)$$

where:
D is the moisture diffusion coefficient, in m$^2$/s;
$\frac{\Delta u}{\Delta x}$ - moisture content gradient over the sample thickness (assuming that drying takes place as consequence of one-dimensional water movement across the timber thickness only, which is the lowest dimension of a industrial timber grade), in 1/m;
*s* - sample thickness, in m.

Considering *w* as the average drying speed over a certain interval of moisture content decrease ($\Delta$U), the corresponding drying time $\tau$ can be estimated as:

$$\tau = \frac{\Delta U}{w} \quad [\mathrm{h}] \qquad (6)$$

or, by replacing the expression (5) of the drying speed (w) in Eq. (6), this becomes:

$$\tau = \frac{\Delta U \cdot s}{D \cdot \frac{\Delta u}{\Delta x}} \cdot 0{,}27 \cdot 10^{-5} \quad [\mathrm{h}] \qquad (7)$$

which shows the moisture diffusion coefficient (*D*) offers a useful way to estimate drying time below the fiber saturation point.

Several researches were carried out in order to experimentally establish its exact values. This is not an easy task, considering that the diffusion coefficient depends on wood density and anatomical pattern (Perre 1997, Fotsing and Tchagang 2005), grain orientation (Mouchot et al. 2006), sapwood/heartwood (Rosenkilde and Glover 2002), wood moisture and wood temperature, as well as on the environmental parameters (Simpson 1993), growth conditions (Cai 2005) or the presence of reaction wood (Tarmian et al. 2012).

Significant contribution regarding the moisture diffusion in beech wood was brought by Mouchot and Zoulalian 2002, Mouchot et al. 2006, Perre et al. 2007.

However, none of the previous researches dealt with the influence of previous steaming upon the moisture diffusivity in beech wood. Dashti et al. (2012) performed a research with pre-steamed Aleppe oak wood (*Quercus infectoria*) and reported significant increase of the diffusion coefficients compared to unsteamed wood. This increase effect applies only to the sapwood samples and is mainly attributed to the change of the chemical composition of wood (the holocellulose content decreased by 4,8%) through the high steaming temperature (160°C). In the heartwood samples, due to the presence of tyloses which prevent steam to enter the inner parts, the diffusion coefficient remained comparable to the one of the control samples.

## OBJECTIVE

The objective of the present research was to estimate the drying time of beech timber, by taking into consideration its thickness, whether it was previously steamed, whether it contains red heart or just white wood. In order to achieve this objective, the moisture diffusion coefficient (*D*) was experimentally determined in steamed and unsteamed beech wood samples originating from the inner side of the log (white wood) and from the outer side (red heart), in all three grain directions, by using four different temperature levels. These experimental data were then used to calculate the drying speed ($w$) and the drying time ($\tau$) as function of all above-mentioned variables. The paper is expected to provide useful information regarding the influence of pre-steaming and the level of drying temperature upon the diffusivity and drying time of beech wood.

## MATERIALS AND METHOD

The moisture diffusion experiment was based on the steady-state hypothesis.

It was carried out with steamed and unsteamed white wood samples (SWW amd UWW), respectively steamed and unsteamed red heart wood samples (SRH and URH) cut from the same beech log (*Fagus sylvatica* L.). A total of 480 cylindrical samples with diameter Φ35mm and 42mm length were cut in rigorous grain direction, so as to have the length strictly oriented in longitudinal (L), radial (R) or tangential (T) direction.

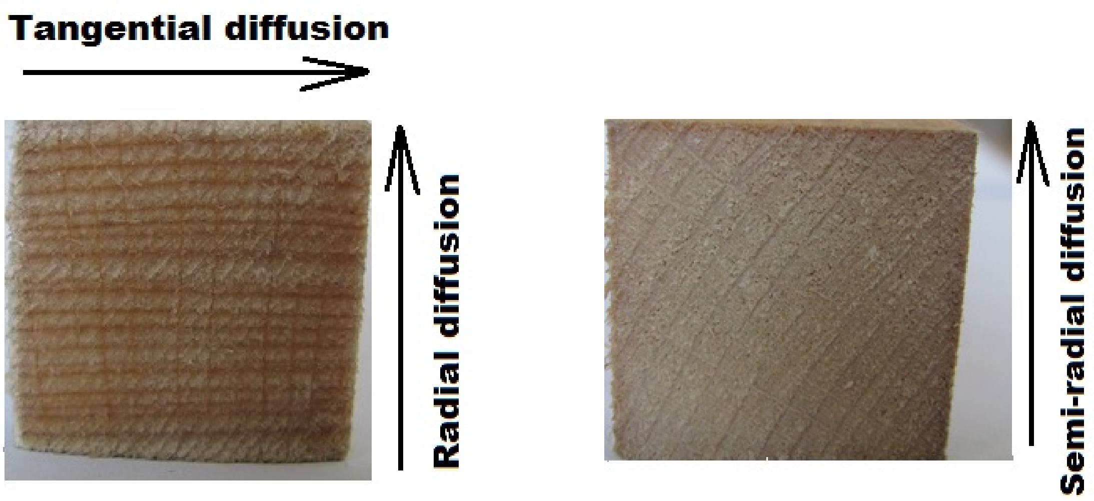
The diffusion coefficients were determined according to ASTM E96:80, by the Water Method. Each sample was introduced in a glass filled with 10mm of distilled water, so as to keep a distance of 19±6mm from the water level (to avoid contact during manipulation). Each glass+wood sample assembly was insulated laterally by means of a rubber tube. The so obtained „cups" were then placed in a dessiccator (Fig. 1), having at the bottom a hygroscopic substance ($CaCl_2$), in order to create at the upper part of the samples an absolute dry atmosphere, while their lower part is exposed to a vapor-saturated atmosphere. A pressure gradient is thus generated in sample length, which will determine the moisture movement of water through the wood sample, from the end exposed to higher moisture concentration (the lower end) towards the „dry" end, exposed to air with zero moisture concentration (the upper end).

***Fig.1.***
***„Cups" for the determination of the moisture diffusion coefficient in beech wood.***

In order to evaluate the influence of temperature upon the water vapor transmission, the dessiccator was then introduced in an electrical oven and kept at constant temperature of 40°C, 60°C, 80°C and 100°C respectively, until the moisture flow became stationary. This moment was established by plotting the weighing results against time; when the curve became straight, it was considered that the moisture flow had become stationary. The water vapor transmission (WVT) was calculated by Eq. (2), by considering $\frac{\Delta M}{\Delta t}$ the slope of the straight line and $A=\pi \cdot (\frac{0{,}035}{2})^2$ =9,62m$^2$.

Hereinafter, the diffusion coefficients in radial and tangential direction were calculated according to Eq. (3), where the moisture content gradient ($\Delta u$) was considered to be the moisture content difference (in %/%) between the two ends of the sample; this was established by cutting each sample into five layers after the experiment and by measuring the moisture content of each layer by the oven-dry method. $\Delta x$ represents the sample length ($\Delta x$=0,042m).

Considering that industrial timber grades are usually semi-radial or semi-tangential (Fig. 2), an average moisture diffusion coefficient ($D_\perp$) was calculated as arithmetic mean between $D_{rad}$ and $D_{tg}$ and then used within Eq. (5) and (6) in order to determine the drying speed and the drying time.



*a. Moisture diffusion in strict radial / tangential direction*

*b. Moisture diffusion in industrial, semi-radial timber grades (D⊥)*

***Fig. 2.***
***Moisture diffusion related to wood grain orientation.***

## RESULTS

The average initial moisture content and oven-dry density of the wood samples is given in Table 1.

*Table 1*
***Initial moisture content and oven-dry density of beech wood samples used within the experiment***

| Wood type | Initial moisture content, % | Oven-dry density, in kg/m$^3$ |
|---|---|---|
| UWW | 8,2±0,5 | 571±18 |
| SWW | 9,2±0,3 | 591±10 |
| URH | 9,3±0,8 | 630±26 |
| SRH | 9,0±0,6 | 662±19 |

The average values of the diffusion coefficients experimentally obtained on sets of 10 samples for each diffusion test are presented in Table 2.

*Table 2*
***Moisture diffusion coefficients of steamed and unsteamed beech wood***

| Wood type | Grain orientation | Moisture diffusion coefficient (*D*), in m$^2$/s, at temperature: | | | |
|---|---|---|---|---|---|
| | | 40°C | 60°C | 80°C | 100°C |
| UWW | L *D*∥ | 118,27 | 414,47 | 1063,34 | 3767,30 |
| | R *Drad* | 6,38 | 27,67 | 63,61 | 360,67 |
| | T *Dtg* | 5,01 | 23,75 | 51,26 | 263,97 |
| | R/T *D*⊥ | 5,69 | 25,71 | 57,43 | 312,32 |
| SWW | L *D*∥ | 101,87 | 310,38 | 792,65 | 2992,73 |
| | R *Drad* | 4,64 | 22,93 | 50,38 | 247,55 |
| | T *Dtg* | 3,41 | 19,33 | 42,19 | 175,80 |
| | R/T *D*⊥ | 4,02 | 21,13 | 46,28 | 211,67 |
| URH | L *D*∥ | 60,70 | 240,09 | 665,07 | 2375,26 |
| | R *Drad* | 3,08 | 18,93 | 41,46 | 172,55 |
| | T *Dtg* | 2,01 | 16,01 | 35,89 | 129,57 |
| | R/T *D*⊥ | 2,54 | 17,47 | 38,67 | 151,06 |
| SRH | L *D*∥ | 36,73 | 190,66 | 437,15 | 1713,70 |
| | R *Drad* | 1,85 | 15,85 | 34,90 | 113,70 |
| | T *Dtg* | 1,36 | 11,51 | 31,08 | 80,98 |
| | R/T *D*⊥ | 1,60 | 13,68 | 32,99 | 97,34 |

The average values of the drying speed computed according to Eq. (5) for timber of different thicknesses are presented in Table 3.

*Table 3*

***Drying speed of beech wood with different thicknesses, at different drying temperatures***

| Thickness, in mm | Wood type | Drying speed, in %/h, at temperature: | | | |
|---|---|---|---|---|---|
| | | 40°C | 60°C | 80°C | 100°C |
| 20mm | UWW | 0,051 | 0,231 | 0,517 | 2,811 |
| | SWW | 0,036 | 0,190 | 0,417 | 1,905 |
| | URH | 0,023 | 0,157 | 0,348 | 1,360 |
| | SRH | 0,014 | 0,123 | 0,297 | 0,876 |
| | | | | | |
| 40mm | UWW | 0,013 | 0,058 | 0,129 | 0,703 |
| | SWW | 0,009 | 0,048 | 0,104 | 0,476 |
| | URH | 0,006 | 0,039 | 0,087 | 0,340 |
| | SRH | 0,004 | 0,031 | 0,074 | 0,219 |
| | | | | | |
| 60mm | UWW | 0,006 | 0,026 | 0,057 | 0,312 |
| | SWW | 0,004 | 0,021 | 0,046 | 0,212 |
| | URH | 0,003 | 0,017 | 0,039 | 0,151 |
| | SRH | 0,002 | 0,014 | 0,033 | 0,097 |
| | | | | | |
| 80mm | UWW | 0,003 | 0,014 | 0,032 | 0,176 |
| | SWW | 0,002 | 0,012 | 0,026 | 0,119 |
| | URH | 0,001 | 0,010 | 0,022 | 0,085 |
| | SRH | 0,001 | 0,008 | 0,019 | 0,055 |

The average values of the drying time ($\tau$) computed according to Eq. (6) for timber of different thicknesses, from an initial moisture content of 30% down to 10% ($\Delta U$=20%) are presented in Table 4.

*Table 4*

***Drying time of beech wood with different thicknesses from 30% to 10% moisture content, at different drying temperatures***

| Thickness, in mm | Wood type | Drying time, in h, at temperature: | | | |
|---|---|---|---|---|---|
| | | 40°C | 60°C | 80°C | 100°C |
| 20mm | UWW | 390 | 86 | 39 | 7 |
| | SWW | 552 | 105 | 48 | 10 |
| | URH | 873 | 127 | 57 | 15 |
| | SRH | 1385 | 162 | 67 | 23 |
| | | | | | |
| 40mm | UWW | 1561 | 346 | 155 | 28 |
| | SWW | 2208 | 421 | 192 | 42 |
| | URH | 3493 | 509 | 230 | 59 |
| | SRH | 5538 | 650 | 269 | 91 |
| | | | | | |
| 60mm | UWW | 3512 | 778 | 348 | 64 |
| | SWW | 4969 | 947 | 432 | 94 |
| | URH | 7859 | 1145 | 517 | 132 |
| | SRH | 12461 | 1462 | 606 | 205 |
| | | | | | |
| 80mm | UWW | 6243 | 1383 | 619 | 114 |
| | SWW | 8834 | 1683 | 768 | 168 |
| | URH | 13971 | 2035 | 919 | 235 |
| | SRH | 22153 | 2599 | 1078 | 365 |

## DISCUSSION

One of the main findings of the present research refers to the influence of drying temperature upon the drying time. The values in Table 4 clearly show that drying beech at 40°C is highly inefficient with timber grades thicker than 20mm, as the drying time exceeds 60 days. The drying time values obtained at 60°C are 4,5 times smaller with white wood samples and up to 8,5 times smaller for the red heart samples than at 40°C. This clearly proofs that breaking the bonds between the bound water and the wooden substance in beech wood requires a temperature of at least 60°C. Applying a drying temperature of 80°C reduces further 2,2 times the drying time compared to 60°C, which is not so spectacular as the previous result. A second spectacular threshold was found between 80°C and 100°C, when the dryng time was 5,4 times reduced with white wood samples and 3 times with the red heart samples when applying 100°C (Fig. 3).

When comparing white wood and red heart one may notice that white wood dries faster than red heart. This fact must be attributed to the difference in wood density. According to the values given in Table 3, the drying speed of white wood is 1,40-2,57 times higher than that of red heart. The higher discrepancies were obtained at 40°C and 100°C (Fig. 4).

The effect of steaming upon the diffusion rate and drying time did not confirm the result obtained by Dashti et al. (2012) with Aleppe oak wood. In fact, the diffusion rate decreased in the present research performed with beech wood, leading thus to 1,20-1,57 longer drying times than for the unsteamed wood samples (Fig. 5). However, in the present research, steaming was performed at much lower temperature (99°C compared to 160°C applied to Aleppe oak) which is probably the reason that no significant changes in the chemical composition of wood were determined, and so, no significant improvement of diffusivity was obtained either.

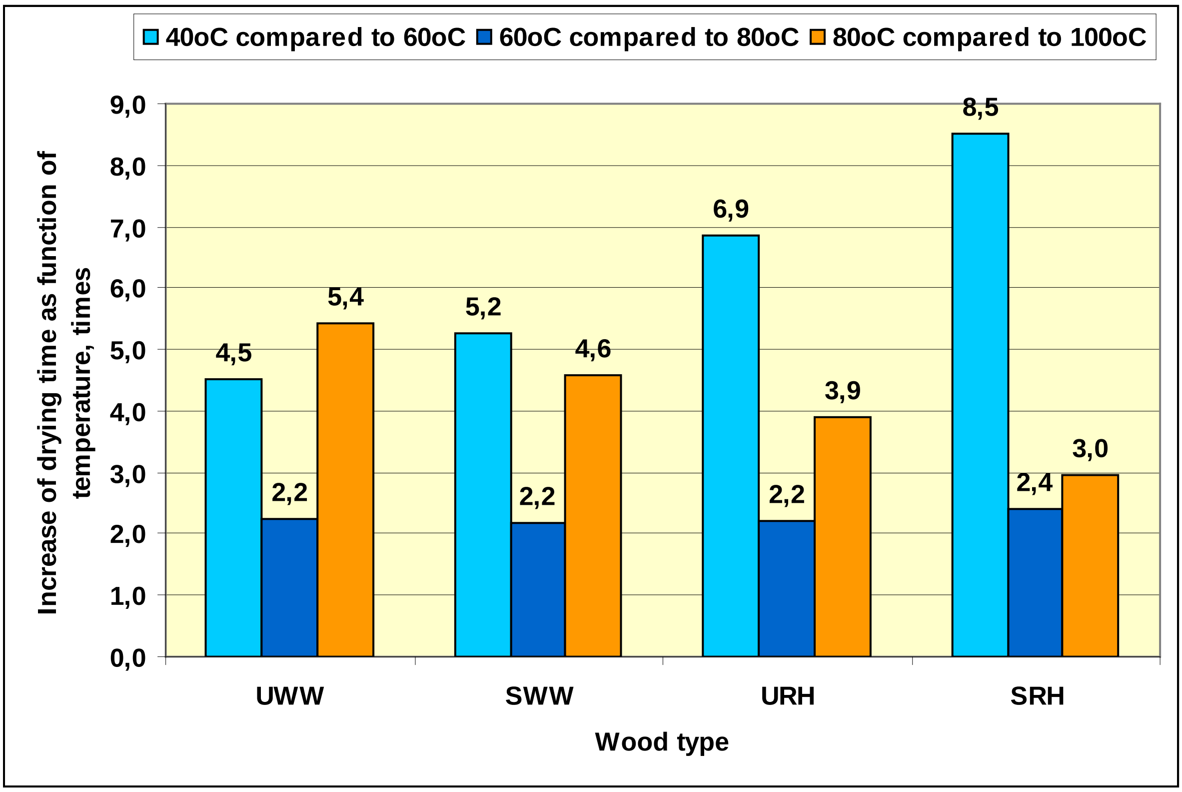


***Fig. 3.***
***Influence of drying temperature upon the drying time of beech wood below fiber saturation point.***

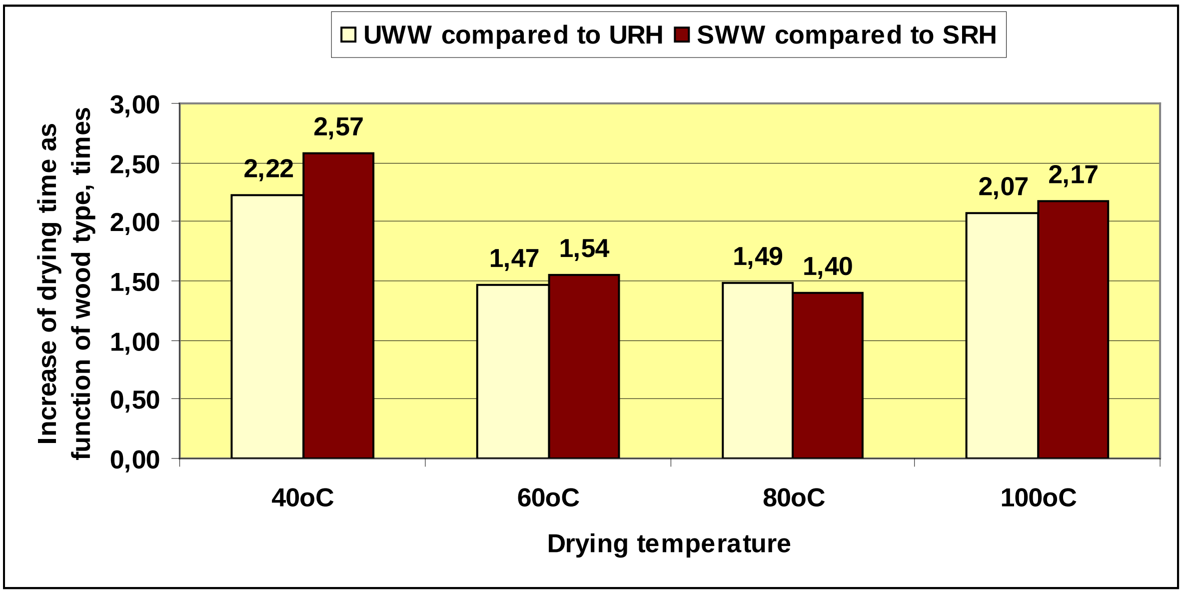


*Fig. 4.*
***Influence of wood type (white wood vs. red heart of beech wood) upon the drying time below fiber saturation point.***

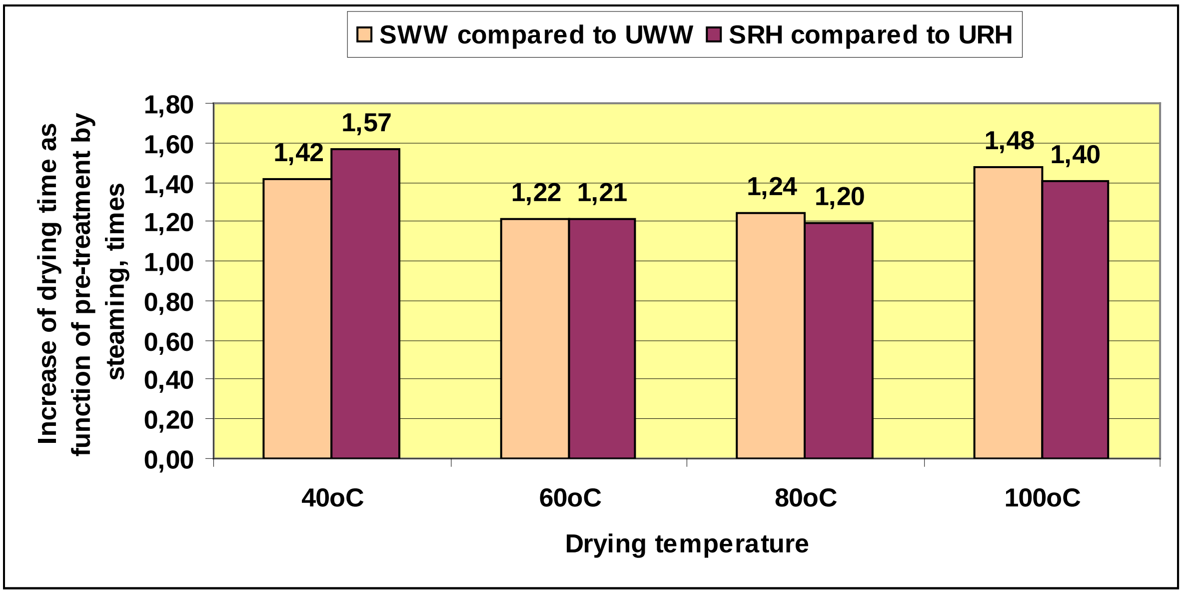


*Fig. 5.*
***Influence of steaming (steamed wood vs. unsteamed wood) upon the drying time of beech wood below fiber saturation point.***

## CONCLUSION

The paper provides interesting information regarding the drying time of beech timber, by taking into consideration its thickness, previous treatment (steamed or not steamed), position from within the cross section of the log (only white wood or with red heart) and the applied drying temperature. Experimentally established moisture diffusion coefficients guarantee the novelty and reliability of the results.

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