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Influence of molar transfer coefficient on pressure distribution in beech lumber during its convective-vacuum drying

Utjecaj molarnog koeficijenta na raspodjelu tlaka u bukovim piljenicama tijekom vakuumskog sušenja

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ABSTRACT • *Using a base system of three differential equations as suggested by Luikov and Mihaylov, a non-linear 2-dimensional mathematical model has been developed and solved for computation of transient distribution of temperature, moisture content and pressure in prismatic wood materials subjected to convective-vacuum drying. The model relates to heat and mass transfer in longitudinal and transversal directions of wood materials.*
This paper presents the influence of the molar transfer coefficient and the direction of steam-air flow to wood fibres on the pressure distribution in beech wood materials during their convective-vacuum drying. The results of computational experiments are graphically presented and analyzed.

Keywords: *vacuum drying, pressure distribution, molar transfer coefficient, specific mass capacity, beech wood*

SAŽETAK • *Na temelju sustava triju diferencijalnih jednadžbi koji su predložili Luikov and Mihaylov (1963), razvijen je i riješen nelinearni dvodimenzionalni matematički model za računanje kratkotrajne raspodjele temperature, sadržaja vode te tlaka u prizmatičnome drvnom materijalu tijekom konvekcijskoga vakuumskog sušenja. Model se odnosi na prijenos topline i mase u longitudinalnome i poprečnom smjeru drvnog materijala.*
U radu se iznosi analiza utjecaja molarnog koeficijenta i smjera strujanja pare odnosno zraka prema smjeru drvnih vlakanaca na raspodjelu tlaka u bukovim piljenicama tijekom konvekcijskoga vakuumskog sušenja. Rezultati računalne analize grafički su prikazani i analizirani.

Ključne riječi: *vakuumsko sušenje, raspodjela tlaka, molarni koeficijent, specifični maseni kapacitet, bukovina*

1 INTRODUCTION
1. UVOD

The convective-vacuum drying of wood materials is a complex process, where the heat and mass transfer take place under pressure, lower than the atmospheric pressure. As a result, 3 types of gradients occur: those of temperature, moisture and pressure.

The speed of this drying process is significantly dependent on the gradient of wood pressure, which is

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influenced by specific gas permeability K_g and the resulting molar transfer coefficient λ_p in correspondence with Darcy's Law.

Luikov and Mihaylov (1963) present Darcy's Law as follows:

$$J = \lambda_p \nabla P, \tag{1}$$

where

$$\lambda_p = k \cdot \frac{d}{1+d}, \tag{2}$$

$$k = \frac{K_g \cdot \rho_g}{\eta_g} \tag{3}$$

The migration of the fluid through capillary-porous media under the influence of the pressure gradient is named differently by different authors: "molar transfer" (Luikov and Mihaylov 1963), "percolation" (Perré 2000) and "bulk flow" (Chen 1997).

Models other than those suggested by Luikov and Mihaylov (1963), which describe the heat and mass transfer in capillary-porous media, calculated by use of coefficient λ_p in equation (2) is also used by G. Shubin (1990) during mathematical modelling of high temperature drying of wood.

During the mathematical description of the process of convective-vacuum drying, Z. Chen (1997) presents Darcy's Law in the following form analogous to equation (2):

$$J = \frac{K_g \cdot \rho_g}{\eta_g} \cdot \frac{P_{avg}}{P} \cdot \frac{dP}{dx}. \tag{4}$$

When steam is transmitted in the wood through the filtration movement of steam-air mixture, the parameters for the steam-air mixture in equations (2) and (3) must be substituted, resulting in the following equation for determining λ_{pva}:

$$\lambda_{pva} = \frac{K_g}{\eta_g} \cdot \rho_g \cdot \frac{d}{1+d}. \tag{5}$$

When the pressure becomes equal or lower than the steam partial pressure in wood during the vacuum drying process, it can be assumed that the steam-air mixture has been completely transformed into steam. In this case, steam parameters for the determination of the molar transfer coefficient λ_{pv} in equations (2) and (3) are substituted and the following equation is obtained (Syuleymanov and Deliiski 2004a):

$$\lambda_{pv} = \frac{K_g}{\eta_g} \cdot \rho_v. \tag{6}$$

No results of theoretical or experimental studies dealing with the influence of the molar transfer coefficient λ_p on the pressure distribution in wood have been published in the reference literature.

Z. Chen (1997) has conducted experiments for the cyclical and uninterrupted convective-vacuum drying of red and white oak, which has different specific gas permeability K_g. The results of the experiments show that high permeable red oak gets dried more intensely and the pressure in this type of wood decreases faster than that of less permeable white oak.

Apart from the parameters of steam-air mixture and pure steam in wood, K_g (and consequently also λ_p) is strongly affected by the direction of the fluid flow toward the wood fibres (Siau 1971, 1984, Chen 1997, Perré 1999, 2000).

P. Perré (2000) has determined that K_g in the longitudinal direction of beech wood is approximately 65 000 times bigger than K_g in the transversal direction. In his experimental studies with red and white oak, Z. Chen (1997) has determined that the transfer of mass (water steam, liquid water) in the transversal direction is almost absent because of incredibly small permeability in the transversal direction in comparison to that in the longitudinal direction during the time of the process of convective-vacuum drying.

The subject of this paper is the simulation study of the so far unknown influence of the molar transfer coefficients λ_{pva} in the hygroscopic diapason of wood on the non-stationary distribution of pressure in wood materials subjected to convective-vacuum drying. We have completed the study by developing and solving a non-linear analytical-experimental model of the observed process.

2 MATHERIAL AND METHODS
2. MATERIJAL I METODE

2.1 Mathematical model of the process of convective-vacuum drying of wood materials
2.1. Matematički model procesa konvekcijskoga vakuumskog sušenja drva

Based on the analysis of the physics of the process of convective-vacuum drying of wood materials, we have defined mathematically the conditions of this process by use of a system of partial differential equations developed by Luikov and Mihaylov (1963). As a result, 1-, 2-, and 3-dimensional non-linear analytical-experimental (Hadjiski, 2003) models have been solved, allowing the calculation of the transient distribution of temperature, moisture content and pressure in different types of wood material subjected to convective-vacuum drying.

For the case often occurring in practice, when the length of the materials $L_w \leq 3.2$ m, and width $B_w \geq (3 \div 4)H_w$, the following 2- dimensional longitudinal section model is applicable:

$$\frac{\partial T}{\partial \tau} = \frac{\lambda_t}{c \cdot \rho_0} \cdot \frac{\partial^2 T}{\partial x^2} + \frac{\lambda_1}{c \cdot \rho_0} \cdot \frac{\partial^2 T}{\partial y^2} + \frac{\varepsilon r}{c} \cdot \frac{\partial U}{\partial \tau}, \tag{7}$$

$$\begin{aligned} \frac{\partial U}{\partial \tau} = {} & D_{gt} \cdot \frac{\partial^2 U}{\partial x^2} + D_{gl} \cdot \frac{\partial^2 U}{\partial y^2} + D_{gt} \cdot \delta \cdot \frac{\partial^2 T}{\partial x^2} + \\ & + D_{gl} \cdot \delta \cdot \frac{\partial^2 T}{\partial y^2} + \frac{\lambda_{pval}}{\rho_0} \cdot \frac{\partial^2 P}{\partial x^2} + \frac{\lambda_{pvat}}{\rho_0} \cdot \frac{\partial^2 P}{\partial y^2}, \end{aligned} \tag{8}$$

$$\frac{\partial P}{\partial \tau} = \frac{\lambda_{\text{pvat}}}{c_{\text{pva}} \cdot \rho_0} \cdot \frac{\partial^2 P}{\partial x^2} + \frac{\lambda_{\text{pval}}}{c_{\text{pva}} \cdot \rho_0} \cdot \frac{\partial^2 P}{\partial y^2} + \frac{T}{P} \cdot \frac{\partial T}{\partial \tau} - \frac{\varepsilon}{c_{\text{pva}}} \cdot \frac{\partial U}{\partial \tau}, \tag{9}$$

with initial conditions

$$T(x, y, 0) = T_0, \tag{10}$$

$$U(x, y, 0) = U_0, \tag{11}$$

$$P(x, y, 0) = P_0 \tag{12}$$

and boundary conditions

$$\alpha \cdot (T_{\text{m}} - T_{\text{s}}) - \lambda \cdot (\nabla T)_{\text{s}} - (1-\varepsilon) \cdot r \cdot \alpha_{\text{U}} \cdot \rho_0 \cdot (U_{\text{s}} - U_{\text{me}}) = 0, \tag{13}$$

$$\begin{aligned} &\alpha_{\text{U}} \cdot \rho_0 \cdot (U_{\text{s}} - U_{\text{me}}) + D \cdot \rho_0 \cdot (\nabla U)_{\text{s}} + \\ &+ D \cdot \rho_0 \cdot \delta \cdot (\nabla T)_{\text{s}} + \lambda_{pva} \cdot (\nabla P)_{\text{s}} = 0, \end{aligned} \tag{14}$$

$$P_{\text{s}} = P_{\text{m}}. \tag{15}$$

Based on critical analysis, for the solution of the model, equations suggested by different authors are used, which describe a portion of the variables in them. We have made the mathematical description of the remaining variables, as well as of the parameters of the processing medium T_{m}, φ_{m} (T_{m} and φ_{m} together define U_{me} in equations (13) and (14)) and P_{m} during the time of convective-vacuum drying of wood materials. The model is non-linear, because a significant portion of the variables in it, constitute non-linear functional dependents on the parameters of T, U and P wood condition.

2.2 Solution of the mathematical model
2.2. Rješenje matematičkog modela

For the solution of the model, an explicit form of the finite-difference method (Deliiski 2004) has been used. For this purpose, the equations (7) ÷ (15) are presented in a form, suitable for programming in the calculation environment of VISUAL FORTRAN PROFESSIONAL, developed by Microsoft and operating under Windows.

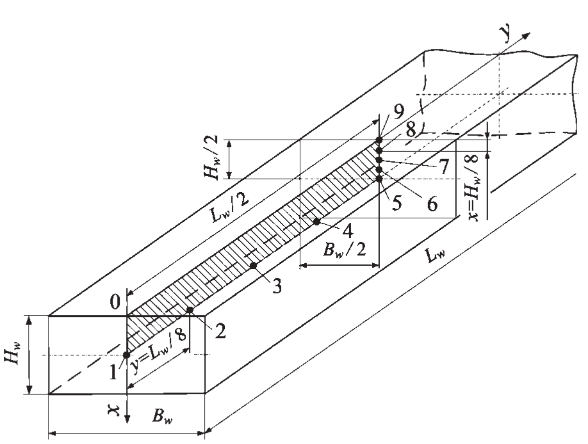

Figure 1 The location of a portion of characteristic points in the longitudinal section of the drying material, in which the distribution of temperature, water content, and pressure is calculated
Slika 1. Smještaj dijela karakterističnih točaka na longitudinalnom odsječku sušenog materijala u kojima je računana raspodjela temperature, sadržaja vode i tlaka

The model has been solved by ¼ of the longitudinal section of the material subjected to drying, which is proportional in respect to the remaining ¾ of the section.

The location of the coordinate axes and a portion of characteristic points on the longitudinal sections, in which the change in T, U and P is calculated during drying, are shown in Fig.1.

3 RESULTS AND DISCUSSION
3. REZULTATI I RASPRAVA

With the help of the model, the changes in T, U and P are studied for beech (*Fagus Silvatica L.*) lumber with $H_{\text{w}} = 0.08$ m, $L_{\text{w}} = 3.2$ m, $\rho_0 = 680$ kg·m^{-3} (Videlov, 2003) and $U = 0.3$ kg·kg^{-1}.

Figure 2 shows the change in T calculated with the model in the wood and on its surface with the input of changes in T_{m}, φ_{m} and P_{m} through the exponential equations during the initial 6 hours of heating and one cycle of vacuuming with a duration of 1 hour and a following 2-hour heating of the materials.

Figures 3 and 4 show the calculated change of P_{m} and P at 4 characteristic points, located in the longitudinal and transverse axes respectively of the longitudinal section of the materials subjected to drying during the time of one cycle of 1 hour vacuuming and a following 2 hours of heating.

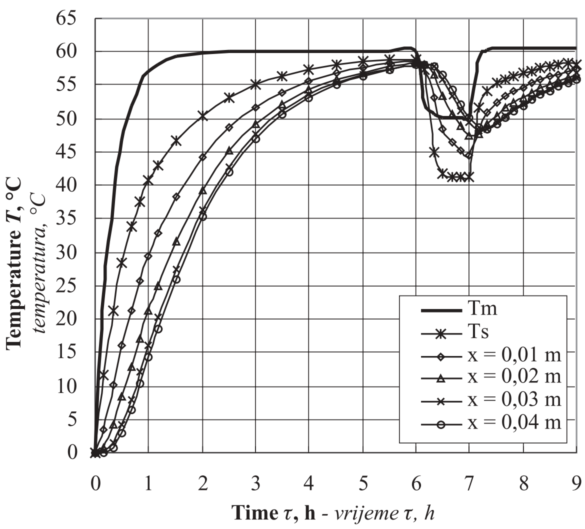

Figure 2 Change in T_{m}, T_{s} and T in the cross axis ($y = 1.6$ m) of beech material subjected to drying
Slika 2. Promjene temperature medija T_{m}, temperature površine drva T_{s} i temperature drva T na poprečnoj osi ($y = 1{,}6$ m) u ovisnosti o vremenu sušenja uzorka od bukovine

Figures 5 and 6 show the change in λ_{pva} at the same characteristic points located in the longitudinal and transversal axes respectively of the section of beech materials subjected to drying during the time of vacuuming and the following heating.

The obtained results lead to the following important conclusions:

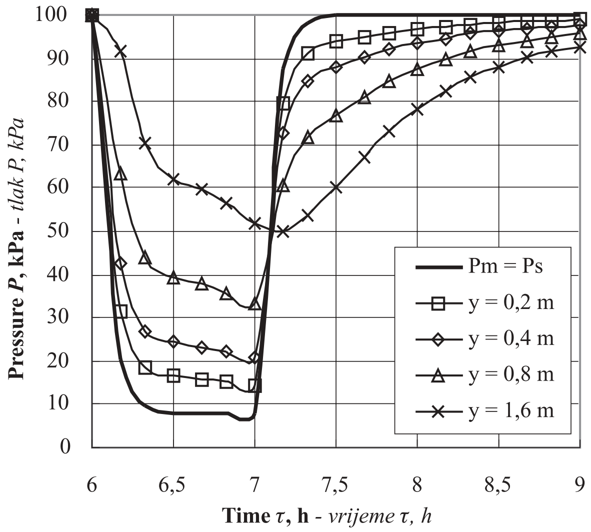

Figure 3 Change in P_m, P_s and P in the longitudinal axis of beech material subjected to drying at x = 0.04 m

Slika 3. Promjene tlaka procesnog medija P_m, tlaka na površini drva P_s i tlaka u drvu P na uzdužnoj osi bukove piljenice izložene sušenju na udaljenosti x = 0,04 m u ovisnosti o vremenu sušenja

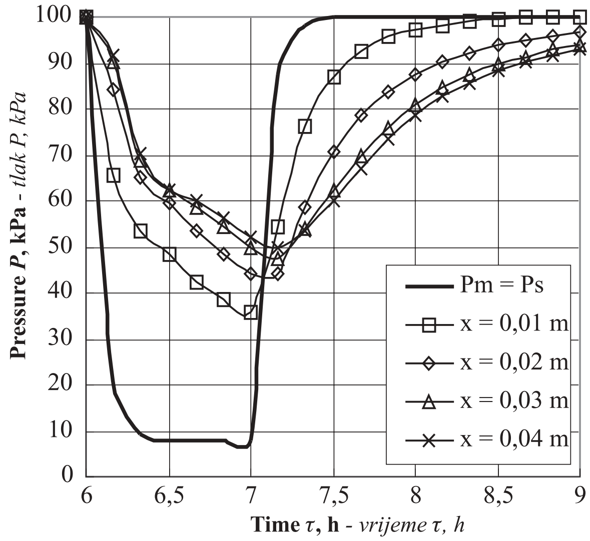

Figure 4 Change in P_m, P_s and P in the transversal axis of beech material subjected to drying at y = 1.6 m

Slika 4. Promjene tlaka procesnog medija P_m, tlaka na površini drva P_s i tlaka u drvu P na poprečnoj osi bukove piljenice izložene sušenju na udaljenosti y = 1,6 m u ovisnosti o vremenu sušenja

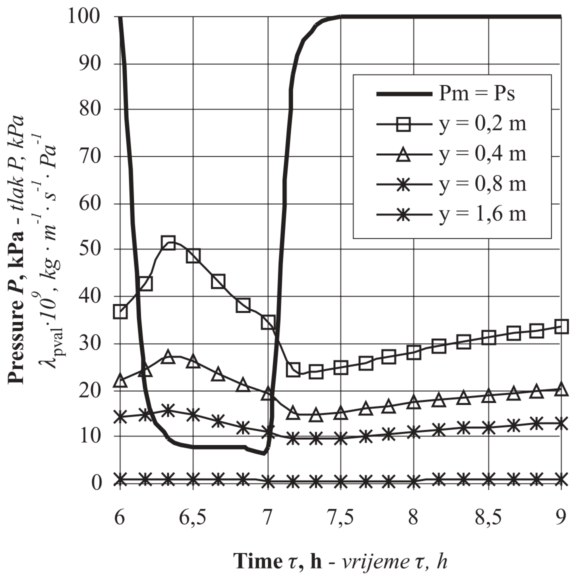

Figure 5 Change in λ_{pva} and P_m in the longitudinal axis of beech material subjected to drying at x = 0.04 m

Slika 5. Promjene tlaka procesnog medija P_m i molarnog koeficijenta λ_{pva} smjese pare i zraka u drvu na uzdužnoj osi bukove piljenice izložene sušenju na udaljenosti x = 0,04 m u ovisnosti o vremenu sušenja

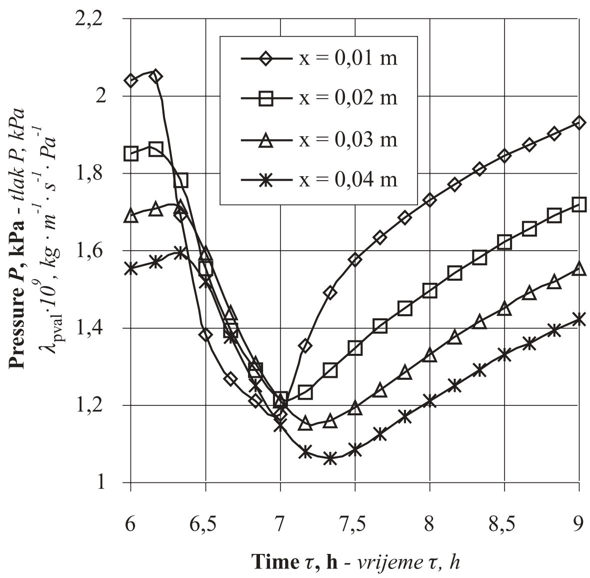

Figure 6 Change in λ_{pva} in the transversal axis of beech material subjected to drying at y = 1.6 m

Slika 6. Promjene molarnog koeficijenta λ_{pva} smjese pare i zraka u drvu na poprečnoj osi bukove piljenice izložene sušenju na udaljenosti y = 1,6 m u ovisnosti o vremenu sušenja

1. The mathematical model, including over 30 coefficients in the system of equations (7) ÷ (15) as obvious functions of the influencing factors, is solved successfully and the results are presented qualitatively similarly to physical process of convective-vacuum drying of wood materials. The calculation with the model of T, U and P distribution in the longitudinal section of materials becomes for the first time mutually-connected to the initial heating and the following cyclical vacuuming and heating of materials, taking into account the mobile boundary of the boiling water in the wood.

2. The model is sensitive to the change in the molar transfer coefficient in longitudinal and transversal directions in wood materials subjected to drying, which is described mathematically (Syuleymanov and Deliiski, 2004a, 2004b) in a function of the current T, U, and P values and at individual points of the longitudinal section of materials, as shown in Figure 1.

3. The results of the studies by P. Perré (2000) give a mathematical description of λ_{pva}, including the relationship between the molar transfer coefficient in the longitudinal and transversal directions showing that they are different for various wood species (for example, for beech wood this relationship is equal to approximately 65000:1), and thus explaining why the pressure distribution in wood materials is strongly affected by

molar transfer coefficient. Consequently, the pressure along wood fibres during vacuuming decreases much faster than the one in transversal direction. In addition, the pressure gradient in the longitudinal direction is much lower than the one in the transversal direction.

4. In the initial period of vacuuming the coefficients λ_{pval} and λ_{pvat} grow (see Fig. 5 and Fig. 6) and this causes a fast decrease in P. After a certain period, the combination of T, U, and P values at different points of the longitudinal section of materials causes a decrease in the values of λ_{pval} and λ_{pvat}, which remains constant until the end of vacuuming, as well as in the initial period of the following cyclical heating. The decrease in λ_{pval} and λ_{pvat} causes a slowing down of the decrease in P. At the end of the 1-hour vacuuming, the pressure in the centre of the beech material (x = 0.04 m and y = 1.6 m) reaches 51.89 kPa. The lowest value of the pressure at that point, which equals 49.98 kPa, is observed 10 minutes after the end of vacuuming and the beginning of the following cyclical heating.

5. During the remaining major part of cyclical heating until its end, the coefficients λ_{pval} and λ_{pvat} grow (see Fig. 5 and Fig. 6) and this causes a smooth increase in P in the materials. At the end of the 2-hour cyclical heating, the pressure in the centre of the beech material reaches up to 92.82 kPa.

4 CONCLUSIONS
4. ZAKLJUČCI

This paper describes the development and solution of a 2-dimensional mathematical model for the computation of transient distribution of temperature, moisture content and pressure in prismatic wood materials subjected to convective-vacuum drying. The model takes into account the physics of the process and relates to the heat and mass transfer in longitudinal and transversal directions of wood materials.

The system of three differential equations in the mathematical model describes the mechanism of heat and mass transfer simultaneously for boiling and non-boiling areas in materials subjected to convective-vacuum drying.

With the help of the model the so far unknown influence of the molar transfer coefficient has been shown as well as of the direction of the steam-air flow to wood fibres on the distribution of pressure in beech wood materials during their convective-vacuum drying.

The development of the model and algorithms and software for its solution is consistent with the possibility for their use in automatic systems with a model predicted control (Hadjiski, 2003) of different heat and mass transfer processes in wood (impregnation, modification, etc.) at atmospheric and lower than atmospheric pressure.

Symbols
Oznake

c specific heat capacity of wood (specifični toplinski kapacitet drva), J·kg^{-1}·K^{-1}

c_{pva} specific mass capacity of wood in relation to the steam-air mixture during its molar transfer process (specifični maseni kapacitet drva u odnosu na smjesu pare i zraka tijekom procesa molarnog prijenosa), m·J^{-1}

d moisture content of the steam-air mixture in wood (sadržaj vode u smjesi pare i zraka u drvu), kg·kg^{-1}

k permeability (permeabilnost), kgm^{-1}·Pa^{-1}·s^{-1}

r latent heat of vaporization (latentna toplina isparavanja), J·kg^{-1}

x transversal coordinate (poprečne koordinate): $0 \le x \le H_w/2$, m

y longitudinal coordinate (uzdužne koordinate): $0 \le y \le L_w/2$, m

B_w width of materials subjected to convective-vacuum drying (širina drvnog materijala za konvektivno vakumsko sušenje), m

D diffusity coefficient (koeficijent difuzije), m^2·s^{-1}

D_{gl} gross wood diffusity coefficient in longitudinal direction (ukupni koeficijent difuzije u uzdužnom smjeru), m^2·s^{-1}

D_{gt} gross wood diffusity coefficient in transversal direction (ukupni koeficijent difuzije u poprečnom smjeru), m^2·s^{-1}

H_w thickness of wood materials subjected to convective-vacuum drying (debljina drvnog materijala za konvektivno vakumsko sušenje), m

J fluid flow (strujanje fluida), kg·s^{-1}

K_g specific gas permeability of wood (specifična plinska permeabilnost drva), m^2

L_w length of materials subjected to convective-vacuum drying (duljina drvnog materijala za konvektivno vakumsko sušenje), m

P pressure in wood (tlak u drvu), Pa

P_{avg} average value of pressure (prosječna vrijednost tlaka), Pa

P_0 initial wood pressure (početni tlak u drvu), Pa

P_m pressure of the processing medium (tlak procesnog medija), Pa

P_N atmospheric pressure (atmosferski tlak): $P_N = 10^5$ Pa

P_s wood surface pressure (tlak na površini drva), Pa

T temperature of wood (temperatura drva), K

T_0 initial temperature of wood (početna temperature drva), K

T_m temperature of the processing medium (temperatura procesnog medija), K

T_{m0} initial medium temperature (početna temperatura medija), K

T_s wood surface temperature (temperatura površine drva), K

U wood moisture content (sadržaj vode u drvu), kg·kg^{-1}

U_0 initial wood moisture content (početni sadržaj vode u drvu), kg·kg^{-1}

U_{fsp} wood moisture content at fibres saturation point (sadržaj vode u drvu kod točke zasićenja vlakanaca), kg·kg^{-1}

U_{me} equilibrium moisture content of the processing medium (ravnotežni sadržaj vode procesnog medija), kg·kg^{-1}

U_s wood surface moisture content (sadržaj vode na površini drva), $kg \cdot kg^{-1}$

Greek symbols
Oznake grčkim slovima

α heat transfer coefficient (koeficijent prijenosa topline), $W \cdot m^{-2} \cdot K^{-1}$

α_U mass transfer coefficient (koeficijent prijenosa mase), $m \cdot s^{-1}$

δ thermo-gradient coefficient of wood (koeficijent termogradijenta drva), K^{-1}

ε phase transition criterion (ratio of vapour diffusion to the total moisture movement: $\varepsilon = 0 \div 1$), mjera promjene stanja (omjer difuzije pare i ukupnog kretanja vode)

η_g dynamic viscosity of gas transferred in wood (dinamički viskozitet plinova u drvu), $Pa \cdot s$

φ relative humidity of steam-air mixture in wood (relativna vlažnost smjese pare i zraka u drvu)

φ_m relative humidity of the processing medium (relativna vlažnost procesnog medija): $\varphi_m = 0 \div 1$

λ thermal conductivity of wood (toplinska vodljivost drva), $W \cdot m^{-1} \cdot K^{-1}$

λ_l thermal conductivity of wood in longitudinal direction (toplinska vodljivost drva u uzdužnom smjeru), $W \cdot m^{-1} \cdot K^{-1}$

λ_t thermal conductivity of wood in transversal direction (toplinska vodljivost drva u poprečnom smjeru), $W \cdot m^{-1} \cdot K^{-1}$

λ_p molar transfer coefficient (molarni koeficijent), $kg \cdot m^{-1} \cdot s^{-1} \cdot Pa^{-1}$

λ_{pv} molar transfer coefficient of steam in wood (molarni koeficijent pare u drvu), $kg \cdot m^{-1} \cdot s^{-1} \cdot Pa^{-1}$

λ_{pva} molar transfer coefficient of steam-air mixture in wood (molarni koeficijent smjese pare i zraka u drvu), $kg \cdot m^{-1} \cdot s^{-1} \cdot Pa^{-1}$

λ_{pval} molar transfer coefficient of steam-air mixture in longitudinal direction of wood (molarni koeficijent smjese pare i zraka u uzdužnom smjeru drva), $kg \cdot m^{-1} \cdot s^{-1} \cdot Pa^{-1}$

ρ_{pvat} molar transfer coefficient of steam-air mixture in transversal direction of wood (molarni koeficijent smjese pare i zraka u poprečnom smjeru drva), $kg \cdot m^{-1} \cdot s^{-1} \cdot Pa^{-1}$

ρ_g density of gas, transferred in wood under pressure gradient (gustoća plina, transportiranog u drvu pod gradijentom tlaka), $kg \cdot m^{-3}$

ρ_0 dry wood density (gustoća suhog drva), $kg \cdot m^{-3}$

ρ_v water steam density (gustoća vodene pare), $kg \cdot m^{-3}$

τ time (vrijeme), s

∇ Nabla operator: $\nabla = \frac{\partial}{\partial x} + \frac{\partial}{\partial y}$

$(\nabla P)_s$ pressure gradient on the surface of wood materials (gradijent tlaka na površini drva), $Pa \cdot m^{-1}$

$(\nabla T)_s$ temperature gradient on the surface of wood materials (gradijent temperature na površini drva), $K \cdot m^{-1}$

$(\nabla U)_s$ moisture gradient on the surface of wood materials (gradijent sadržaja vode na površini drva), $kg \cdot kg^{-1} \cdot m^{-1}$

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