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COMPUTATION AND 3D VISUALIZATION OF THE TRANSIENT TEMPERATURE DISTRIBUTION IN LOGS DURING STEAMING

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ABSTRACT

A two-dimensional mathematical model has been created, solved, and verified for the transient non-linear heat conduction in frozen and non-frozen logs at arbitrary, encountered in the practice as initial and boundary conditions during the steaming process of wood. The model takes into account the fiber saturation point of each wood species and the specific heat capacity of the wood itself and the ice contained in it, which has been formed by the freezing of the free, as well as of the hygroscopically bound water. It has been solved by the usage of an explicit form of the finite-difference method, where the distribution of the temperature field in all points of the volume of the log is calculated for the first time only with one system of equations.

The paper presents solutions of the model and the 3D visualization of the obtained calculated results. The influence of initial wood temperature on the temperature distribution through the longitudinal section of beech logs during their steaming at 80 °C is studied.

The postprocessor application, that has been used for color plots visualization of 2D transient temperature distribution, incorporates. NET and advanced graphics visualization technologies. It has capabilities to show and store results in different forms, including color maps, contour maps and vectors.

Key words: wood, logs, modeling, heating, temperature distribution, visualization, steaming.

INTRODUCTION

For the optimization of the control of log heating process in veneer and plywood mills, it is required that the distribution of the temperature field in logs at every moment of the process is known.

Considerable contribution to the calculation of non-stationary distribution of temperature in frozen and non-frozen logs and to the duration of the heating process has been made by H. P. Steinhagen. For this purpose, he, alone, (STEINHAGEN 1986, 1991) or with co-authors (STEINHAGEN *et al.* 1987, STEINHAGEN and LEE 1988) has created and solved a 1-dimensional, and later a 2-dimensional (KHATTABI and STEINHAGEN 1992, 1993, 1995) mathematical model, whose application is limited by $u \geq 0{,}3$ kg·kg^{-1}.

These models contain two systems of equations, one of which is used for the calculation of the change in temperature along the axis of the log, and the other – for the calculation of the temperature distribution in the remaining points of its volume.

This paper presents the creation, verification and solutions of a 2-dimensional mathematical model of a transient non-linear heat conduction in frozen and non-frozen logs, where the complications and incompleteness in existing analogous models have been overcome. The paper presents and visualizes also the results from 3D simulative investigation of the impact of the initial wood temperature, while there is no ice present in the wood, on the temperature distribution across the longitudinal section of beech logs during the steaming process.

MATHEMATICAL MODEL FOR THE HEATING OF LOGS

The process of heat transfer in logs can be described by a non-linear differential equation of thermo-conductivity, which in polar coordinates takes the following form (DELIISKI 1979, 2009):

$$\rho_{\mathrm{w}} c_{\mathrm{we}} \frac{\partial T(r,z,\tau)}{\partial \tau} = \lambda_{\mathrm{wr}} \left[\frac{\partial^2 T(r,z,\tau)}{\partial r^2} + \frac{1}{r} . \frac{\partial T(r,z,\tau)}{\partial r} \right] + \frac{\partial \lambda_{\mathrm{wr}}}{\partial T} \left[\frac{\partial T(r,z,\tau)}{\partial r} \right]^2 + \\ + \lambda_{\mathrm{wz}} \frac{\partial^2 T(r,z,\tau)}{\partial z^2} + \frac{\partial \lambda_{\mathrm{wz}}}{\partial T} \left[\frac{\partial T(r,z,\tau)}{\partial z} \right]^2 \tag{1}$$

with an initial condition

$$T_{\mathrm{w}}(r,z,0) = T_{\mathrm{w0}}, \tag{2}$$

and boundary conditions

$$T_{\mathrm{w}}(0,z,\tau) = T_{\mathrm{w}}(r,0,\tau) = T_{\mathrm{m}}(\tau). \tag{3}$$

For the solution of the system of equations (1) to (3), a mathematical description of the physical quantities in its thermo-physical characteristics of the wood, c_{we}, λ_{wr}, λ_{wz}, and of its density, ρ_{w}, is needed.

Equations in (DELIISKI 1990, 2003, 2004) present a mathematical description of the effective specific heat capacity coefficient, c_{we}, of wood as a sum of the capacities of wood itself, c_{w}, ice created in it by freezing of free water, c_{fw}, and hygroscopically bound water, c_{bw}.

Equations in (DELIISKI 1994, 2003) present a mathematical description of the density of wood, ρ_{w}, and of its thermal conductivity λ_{w} in each anatomical direction.

COMPUTATION OF THE TEMPERATURE DISTRIBUTION IN LOGS DURING THEIR HEATING

The following system of equations has been derived by passing to final increases in equation (1) by the usage of an, formerly described by (DELIISKI 1977, 2003), explicit form of the finite-difference method and taking into account the mathematical description of the thermal conductivity λ_{w} in different anatomical directions:

$$T_{i,k}^{n+1} = T_{i,k}^{n} + \frac{\Delta\tau b \lambda_{\mathrm{w0r}}}{\rho_{\mathrm{w}} c_{\mathrm{we}} \Delta r^2} \left\{ \begin{array}{l} \left[1 + \beta\left(T_{i,k}^{n} - 273{,}15\right)\right] \left[\begin{array}{l} T_{i-1,k}^{n} + T_{i+1,k}^{n} + K_{\mathrm{wpr}}\left(T_{i,k-1}^{n} + T_{i,k+1}^{n}\right) - \\ \left(2 + 2K_{\mathrm{wpr}}\right) T_{i,k}^{n} + \frac{1}{i-1}\left(T_{i-1,k}^{n} - T_{i,k}^{n}\right) \end{array} \right] + \\ + \beta\left[\left(T_{i-1,k}^{n} - T_{i,k}^{n}\right)^2 + K_{\mathrm{wpr}}\left(T_{i,k-1}^{n} - T_{i,k}^{n}\right)^2\right] \end{array} \right\} \tag{4}$$

with an initial condition

$$T_{i,k}^{0} = T_{\mathrm{w0}}, \tag{5}$$

and a boundary condition

$$T_{0,k}^{n} = T_{i,0}^{n} = T_{\mathrm{m}}(\tau) \ . \tag{6}$$

The size of the interval between time levels $\Delta\tau$ is determined from the condition of stability, needed for the solution of the system of equations (4) ÷ (6) (DELIISKI 1977, 2003).

The presentation of the non-linear particular differential equation (1) from the mathematical model through its discrete analogue (4) corresponds to the setting shown in Fig. 1. It is a setting of the coordinate system and the positioning of the nodes in the mesh, in which the distribution of the temperature in the log is calculated.

The calculation mesh for the solution of the model through the finite-difference method is built on a ¼ part from the longitudinal section of the log, because of its symmetry with the remaining ¾ parts of this section.

The setting of the coordinate system, shown in Fig. 1 allows, with the help of only one system of equations (4), to calculate the change of temperature in any network node of the volume of the log at the moment $(n + 1).\Delta\tau$ using the already calculated values of T at the preceding moment $n.\Delta\tau$.

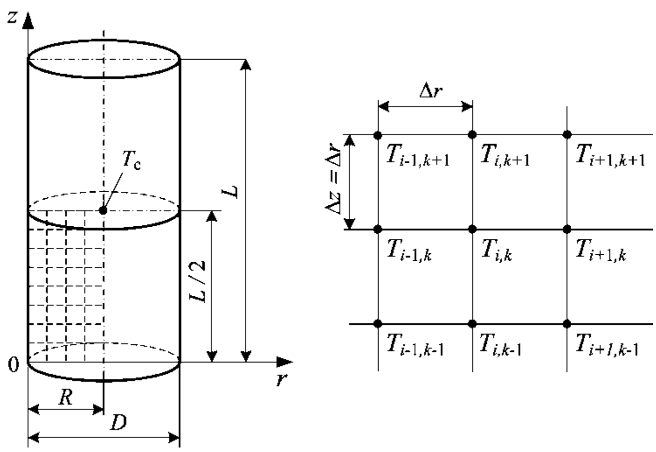

Fig. 1 Positioning of the mesh nodes in a discretized log.

We performed wide experimental studies for the determination of a 1- and 2-dimensional distribution of temperature in the volume of frozen and non-frozen pine, beech, and poplar logs. It has been determined that the coefficient K_{wpr} has the following values: for pine $K_{wpr} = 2.37$, for beech $K_{wpr} = 1.78$, and for poplar $K_{wpr} = 1.96$.

RESULTS AND DISCUSSION

With the help of the model, the 2D changes in t are studied for non-frozen beech logs with $D = 0.40$ m, $L = 0.80$ m, $u = 0.6$ kg·kg^{-1} and initial wood temperature $t_{w0} = 0$°C or $t_{w0} = 20$ °C, during their 20 h steaming at $t_m = 80$ °C.

The changes in t_m and t_w in 4 characteristic points on the longitudinal section with coordinates (R/2, L/4), (R, L/4), (R/2, L/2) and (R, L/2 – central point of the section) are shown in Fig. 2 and 3. The increase of t_m from the value of $t_{m0} = t_{w0}$ to $t_m = 80$ °C goes exponentially with a time constant, which is equal to 1800 s. This increase of t_m at the beginning of the log steaming process can be seen in the Fig. 2 and 3.

Simulations of heat transfer in the radial and longitudinal directions are displayed by a series of 3D graphs and 2D contour plots (Fig. 4 and 5).

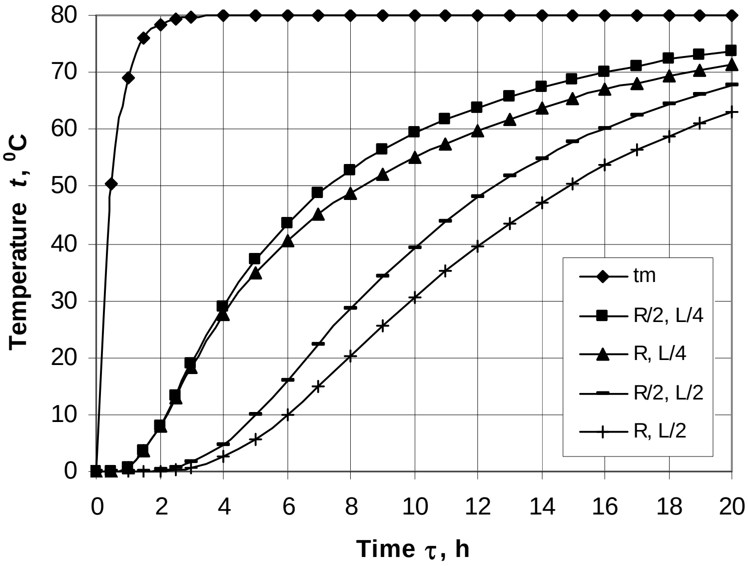

Fig. 2 Change in t of beech logs with D = 0.4 m, L = 0.8 m, u = 0.6 kg·kg^{-1} and t_{w0} = 0 °C.

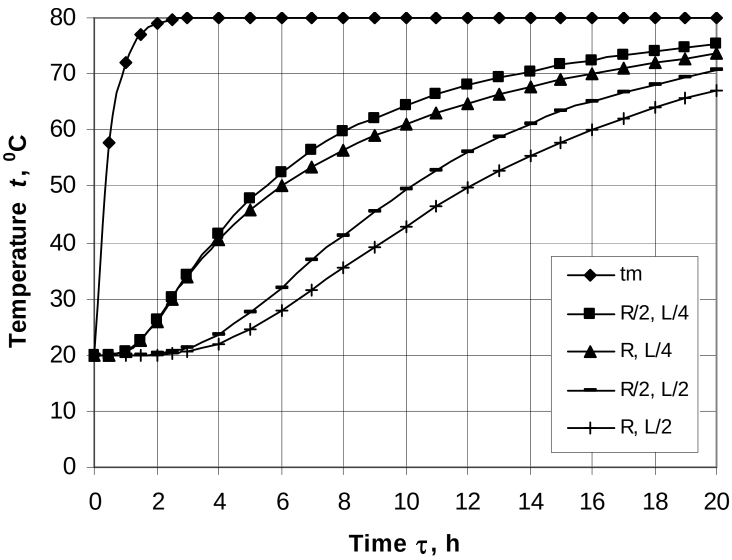

Fig. 3 Change in t of beech logs with D = 0.4 m, L = 0.8 m, u = 0.6 kg·kg^{-1} and t_{w0} = 20 °C.

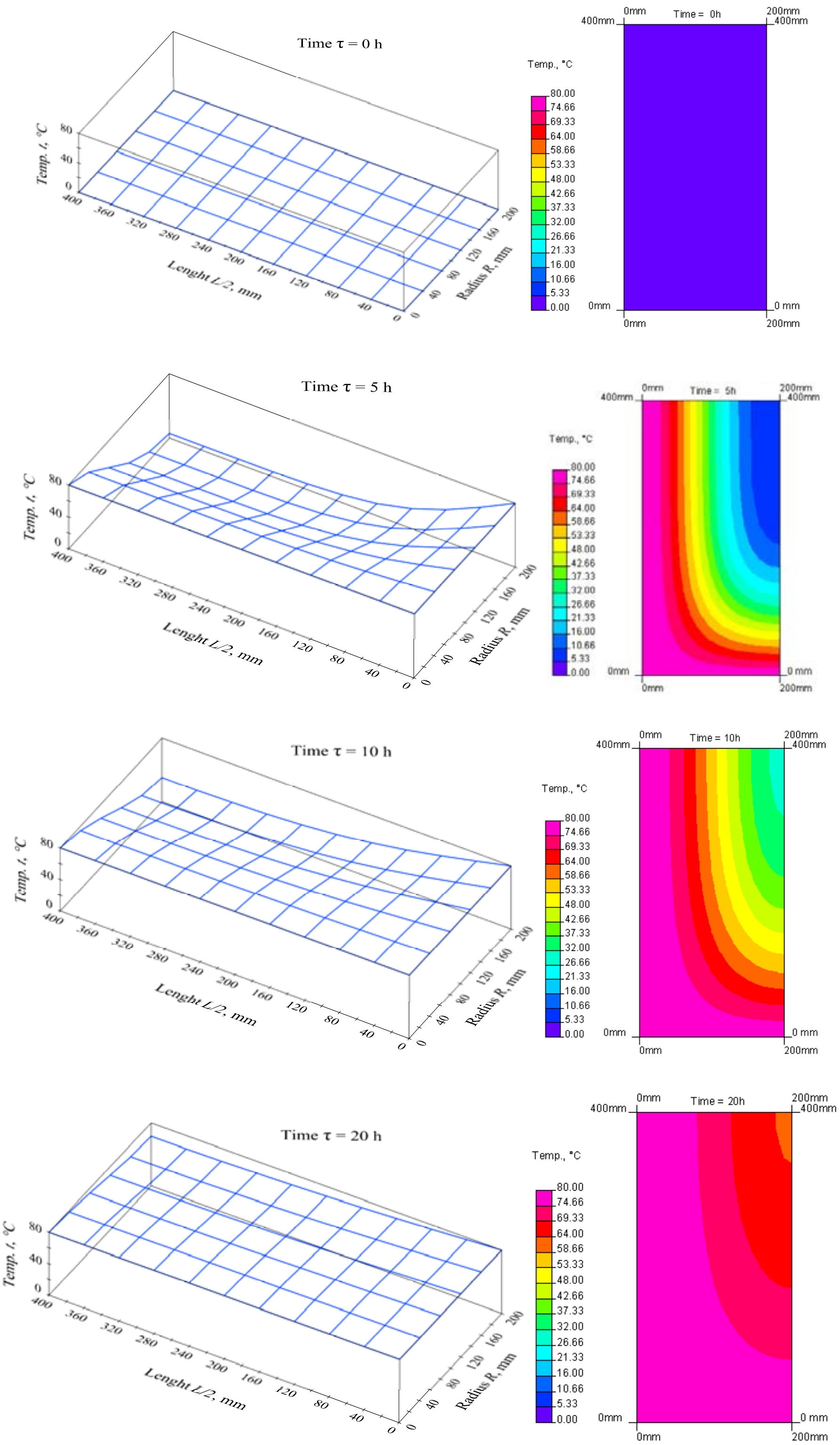

Fig. 4 3D graphics and 2D contour plots for the temperature distribution in time in ¼ of longitudinal section of steamed beech log with D = 0.4 m, L = 0.8 m, u = 0.6 kg·kg^{-1} and t_{w0} = 0 °C.

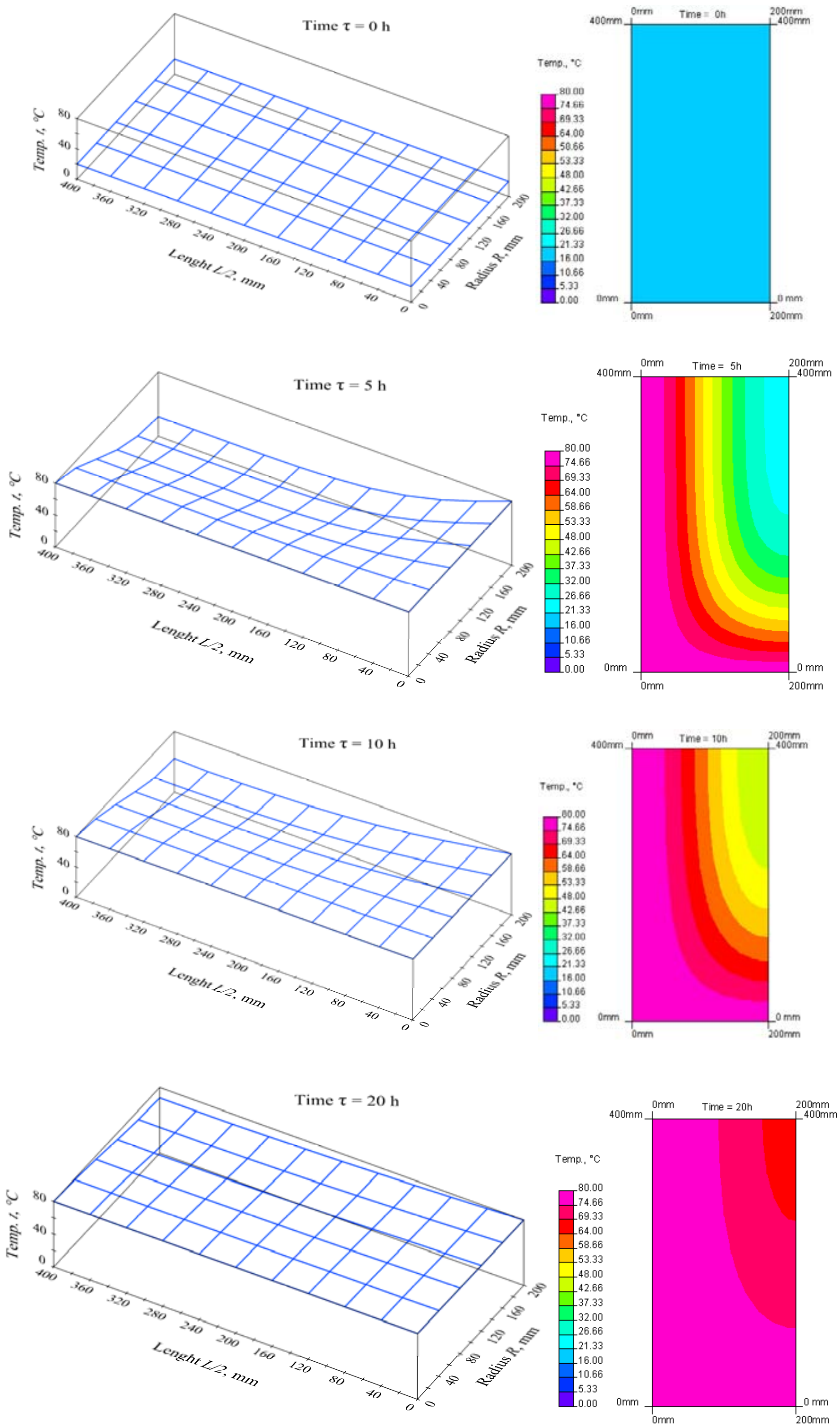

Fig. 5 3D graphics and 2D contour plots for the temperature distribution in time in ¼ of longitudinal section of steamed beech log with D = 0,4 m, L = 0,8 m, u = 0,6 kg·kg^{-1} and t_{w0} = 20 °C.

Transient temperature distribution changes are clearly observable in the 3D graphical presentations (left columns of fig. 4 and 5). 2D contour plots for the results from the simulation are more for qualitative than quantitative observations of the heating process of logs (right columns of Fig. 4 and 5).

At the beginning of the heating process during steaming (Time = 0 h), the temperature is uniformly distributed with the specified initial temperature of the logs (0°C or 20 °C). Within a very short time, the temperature on the surface and at the edge of the logs increases sharply to equilibrate with the external temperature of the steaming medium t_m due to the very high heat exchange between this medium and wood (TREBULA & KLEMENT 2002).

In the graphs, it is clearly shown that the heat flow transported from the outside to the inside with the whole temperature profiles had increased in time until reaching equilibrium with the temperature of the steaming medium (Time = 20 h).

The temperature increased quickly at the beginning of the heating process with a steep temperature gradient in both directions (Time = 5 h), and then slowed down due to the small temperature difference within the log. It can be seen that the temperature increased faster in the longitudinal direction than in the radial direction due to the higher thermal conductivity value for the longitudinal direction. The difference is significant enough since the ratio of the longitudinal over radial thermal conductivity values used in the simulation for the beech wood is 1.78 : 1.00 (DELIISKI 2003). This faster longitudinal heat transfer is clearly seen during the early heating period (Time = 5 h). At the end of the simulations the temperature within the log became almost uniformly distributed as shown in the Figure 2, 3, 4 and 5 (Time = 20 h).

Preparation of postprocessor results in the form of static 2D graphical images (right columns on Fig. 4 and 5) is made by using self-developed software tools described in detail in (MILTCHEV 1999, MILTCHEV *etc*. 2000, YATCHEV *etc*. 2001). They are a part of research aimed to facilitate CAD of electric apparatus and other technical devices that involve in their design a different field analysis of matters and develop general framework application for these purposes. Main features of these tools include postprocessor visualizations of different kinds of results from numerical computations based on the use of the Finite Element Method, Finite Difference Method and Boundary Integral Equation Method in 2- and 3-dimensional steady-state or transient field cases. Several approaches for high-quality postprocessor visualizations are integrated with different transparency levels and vector plots. Final results also include a model geometry drawing and meshes correspondent to chosen numerical computation method can be represented in the form of static images or animations for better analysis of studied objects.

CONCLUSIONS

All 3D graphs in this paper were plotted in AutoCAD, which has a good visualization effect for the model output. The 2D contour color plots can be displayed not only individually at each time step of the steaming process for detailed examination, but they can also be displayed together as an animation for the overall trend observation, which will be very helpful for the industry operators to easily foresee the overall changes of the process.

The 3D graphs and 2D contour plots for temperature profiles are powerful graphical tools that provide a better understanding of the relative change and changing patterns. However, it is difficult to analyze the details of the change and compare the heat transfer in the two directions. The computational results gained by solving of the mathematical model of the transient non-linear heat conduction in logs can be used for such analyses.

Symbols:

c - specific heat capacity [$W \cdot kg^{-1} \cdot K^{-1}$],
D - diameter [m],
L - length [m],
r - radial coordinate: $0 \leq r \leq R$ [m],
R - radius [m],

T - temperature [K],
t - temperature [°C],
u - moisture content [kg·kg^{-1} = %/100],
z - longitudinal coordinate: $0 \leq z \leq L/2$ [m],
λ - thermal conductivity [W·m^{-1}·K^{-1}],
ρ - density [kg·m^{-3}],
τ - time [s],
Δr - distance between mesh points in space coordinates [m],
$\Delta\tau$ - interval between time levels [s].

Subscripts:
bw - bound water
c - center (of logs)
fw - free water
i - nodal point in radial direction: 1, 2, 3, …, ($R/\Delta r$)+1
k - nodal point in longitudinal direction: 1, 2, 3, …, ($L/2\Delta r$)+1
m - medium
0 - initial (at 0 °C for λ)
p - parallel to the fibers
pr - parallel to the radial
r - radial direction (radial to the fibers)
w - wood
we - wood effective (for specific heat capacity)
z - longitudinal direction

Superscript:
n - time level 0, 1, 2, …

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