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Specific Heat Capacity of Wood

Specifični toplinski kapacitet drva

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ABSTRACT • *Specific heat capacity is defined as the amount of heat that a kilogram of a given substance is required to absorb in order to increase its temperature by one degree. The temperature of a given substance can change either at constant pressure or at constant volume, so we differentiate between specific heat capacity at constant pressure (c_p) and specific heat capacity at constant volume (c_v). When doing research into the heat properties of wood, the quantity that most frequently remains constant is pressure, thus restricting our study on specific heat capacity to c_p. This paper provides an overview of the research that has so far been carried out into the specific heat capacity of wood depending on the temperature and moisture content. An analytical and graphical comparison has been performed of the results published in the Wood Industry Manual (1967) (DIP), Wood Handbook (1999) (WH) and work published by Deliiski (2012) (DEL).*

Key words: *specific heat capacity, wood, moisture content, temperature*

SAŽETAK • *Specifični toplinski kapacitet definiramo kao količinu topline koju kilogram neke tvari treba primiti da bi povećao svoju temperaturu za jedan stupanj. Temperatura neke tvari može se mijenjati uz konstantan tlak ili konstantan volumen, pa razlikujemo specifični toplinski kapacitet pri konstantnom tlaku (c_p) i specifični toplinski kapacitet pri konstantnom volumenu (c_v). Pri ispitivanju toplinskih svojstava drva najčešće je tlak veličina koja ostaje konstantna, zbog čega se naša razmatranja specifičnoga toplinskog kapaciteta ograničavaju na c_p. U radu su prikazani rezultati dosadašnjih istraživanja c_p drva u ovisnosti o temperaturi i sadržaju vode. Obavljena je analitička i grafička usporedba rezultata objavljenih u Drvnoindustrijskom priručniku (1967.) (DIP), Wood Handbooku (1999.) (WH) i radu Deliiskog (2012.) (DEL).*

Ključne riječi: *specifični toplinski kapacitet, drvo, sadržaj vode, temperatura*

1 INTRODUCTION
1. UVOD

The thermal properties of wood are essential physical properties, especially in the processes of drying, producing heat energy by combustion and other processes, which include the transfer of heat through wood. The thermal properties of wood are as follows: specific heat capacity (c), coefficient of thermal conductivity (k) and thermal diffusivity (α). These three properties of wood are interconnected by the expression:

$$\alpha = \frac{k}{c \cdot \rho} \qquad (1)$$

where:
α - thermal diffusivity, $m^2 \cdot s^{-1}$,
k - coefficient of thermal conductivity, W/m·K,
c - specific heat capacity, J/kg·°C,
ρ – density, $kg \cdot m^{-3}$.

Wood, being a porous biomaterial, contains small holes that greatly influence the mechanism of heat transfer, and therefore also the specific heat capacity. Generally speaking, wood is a porous system composed of gas (air), liquid (water) and solid matter (wood). Water can be bound or free, and appears in a solid or liquid state (Chudinov, 1968; Twardowski *et al.*, 2006). The maximum amount of bound water in

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wood corresponds to its maximum hygroscopy, i.e. the moisture that the wood absorbs when the relative humidity of air equals 100 %. Maximum hygroscopy is called the fiber saturation point (u_{fsp}). The fiber saturation point depends on the type and density of wood.

In view of the structure of wood, it is considered that the specific heat capacity of wood (c_{pw}) is a sum of the specific heat capacity of a dry wood substance (c_{p0}), the specific heat capacity of free water (c_{pfw}) and the specific heat capacity of bound water (c_{pbw}) (Deliiski, 2012).

$$c_{pw} = c_{p0} + c_{pfw} + c_{pbw} \quad (2)$$

where:
c_{pw} - specific heat capacity of wood, J/kg·°C,
c_{p0} - specific heat capacity of wood of dry wood substance, J/kg·°C,
c_{pfw} - specific heat capacity of free water, J/kg·°C,
c_{pbw} - specific heat capacity of bound water, J/kg·°C.

If the volume of water is below the fiber saturation point, all of the water is bound, thus reducing the aforementioned expression to:

$$c_{pw} = c_{p0} + c_{pbw} \quad (3)$$

The specific heat capacity of free and bound water depends on the state of matter. Free and bound water change their state of matter at different temperatures. Free water in wood changes its state of matter in a temperature range of -2 °C to -0.1 °C, depending on the concentration of dissolved sugar in water (Kubler *et al.,* 1964; Chudinov, 1968), whereas bound water undergoes only a partial phase change in a wide temperature range at temperatures lower than -2 °C.

2 SPECIFIC HEAT CAPACITY OF DRY WOOD SUBSTANCE
2. SPECIFIČNI TOPLINSKI KAPACITET SUHE DRVNE TVARI

Over the course of the twentieth century, a lot of researchers dealt with the issue of the specific heat capacity of dry wood substance (c_{p0}). The main reference point in this area is Dunlop's paper from 1912. In this paper, the c_{p0} is determined by means of a modified Bunsen ice calorimeter. For the purposes of the experiment, the samples were cylindrical in shape, between 3 cm and 9 cm in length, 1.7 cm in base diameter. Out of a total of 110 samples, using 20 different wood species, varying from 0.23 and 1.10 in specific weight, Dunlop determined the specific heat capacity of dry wood substance in a temperature range of 0 °C to 112 °C. These results led to the conclusion that specific heat capacity does not depend on wood species or bulk density. The measurement results showed a linear dependence of specific heat capacity on the temperature ranging from 0 °C to 100 °C, as demonstrated by equation (4). On the basis of the data obtained by measurement, the value of constant *A* and *B* in equation (4) was determined. In the temperature range of 100 °C to 112 °C no connection between c_{p0} and temperature was established; on the basis of the data obtained by measurement, the average specific heat capacity for the given temperature interval was determined by means of equation (5) and it is 1.3688 kJ/kg·°C.

$$\{c_p\}_{J/kg\cdot°C} = A + B\cdot\{t\}_{°C} \quad (4)$$

where:
A - constant that represents specific heat capacity at 0 °C,
B - constant that represents the slope of a line,
t - temperature.

$$\bar{c}_p = \frac{\int_{t_0}^{t_1} c_p}{t_1 - t_0} \quad (5)$$

where: $\bar{c}_p$ - mean specific heat capacity, J/kg·°C,
c_p - specific heat capacity, J /kg·°C,
t_0 - initial temperature, °C,
t_1 - final temperature, °C.

Dunlop (1912), Volbehr (1896) and Koch (1969) measured the c_{p0} for several types of wood in a temperature range of 0 °C to 100 °C, while Kanter (1957) measured the specific heat capacity in a temperature range of -40 °C to 100 °C. The data obtained by the aforesaid authors showed a linear dependence of c_{p0} on temperature. On the basis of the data obtained by measurement, coefficients *A* and *B* (Table 1) in equation (4) were determined. Coefficient *A* represents c_{p0} at the temperature of 0 °C, and coefficient *B* determines the slope of the line. These results led to the conclusion that c_{p0} does not depend on the wood species, density or specific weight.

Table 1 clearly shows that the data published by certain researchers (Dunlop, 1912; Volbehr, 1896; Koch, 1969) are only slightly different, while the data of the research done by Kanter (1957) coincides closely with the other authors in constant *B*, whereas the specific heat capacity at 0 °C is significantly different from the values obtained by the other authors. However, apart from Kanter (1957), none of the other au-

Table 1 Comparison of constants *A* and *B* in equation (4), average specific heat capacity of dry wood substance $\bar{c}_{p_{01}}$ in a temperature range of 0 °C to 100 °C and average specific heat capacity of dry wood substance $\bar{c}_{p_{02}}$ in a temperature range of -40 °C to 100 °C according to the research by Dunlop (1912), Volbehr (1896), Koch (1969) and Kanter (1957)
Tablica 1. Usporedba konstanti *A* i *B* u jednadžbi (4), srednji specifični toplinski kapacitet suhe drvne tvari $\bar{c}_{p_{01}}$ u temperaturnom rasponu od 0 do 100 °C i srednji specifični toplinski kapacitet suhe drvne tvari $\bar{c}_{p_{02}}$ u temperaturnom rasponu od -40 do 100 °C prema istraživanjima Dunlopa (1912.), Volbehra (1896.), Kocha (1969.) i Kantera (1957.)

Author / *Autor*	*A*	*B*	$\bar{c}_{p_{01}}$(0 °C - 100 °C), kJ/kg·°C	$\bar{c}_{p_{02}}$(-40 °C - 100 °C), kJ/kg·°C
Dunlop	1.1136	0.004856	1.3564	1.2592
Volbehr	1.0841	0.005060	1.3371	1.2359
Koch	1.1097	0.004202	1.3198	1.2357
Kanter	1.5488	0.005023	1.7999	1.6994

thors provides such high values of the specific heat capacity at the temperature of 0 °C.

It should be noted that Wilkes and Wood (1949) determined the average specific heat capacity of 1.427 kJ/kg·°C of a fiberboard, the density of which was 0.232 g/cm³, in a temperature range of 27 °C to 100 °C.

For the same temperature interval, the result of 1.421 kJ/kg·°C is obtained by the Dunlop equation (1912), which differs slightly from Wilkes and Wood. Using the Kirsher method of measuring the specific heat capacity, Kühlman (1962) obtained values very similar to those obtained by Dunlop. Different sample preparations and use of different measuring devices provide an explanation for the subtle differences in the results.

Several authors (Brown *et al.*, 1952; Emchenko, 1958; Tiemann, 1951) misquote Dunlop by stating that constant *A* is 0.946 kJ/kg·°C (0.226 kcal/kg·°C) instead of 1.1134 kJ/kg·°C (0.266 kcal/kg·°C).

2.1 Specific heat capacity of wood
2.1. Specifični toplinski kapacitet drva

Volbehr (1896) determines the average specific heat capacity of wood fibers $\overline{c}_{pw}$ in a temperature range of 0 °C to 100 °C, with the wood moisture content (*u*) varying between 0 % and 30 %. In the said temperature range and moisture content, the $\overline{c}_{pw}$ was higher than the $\overline{c}_{p0}$ of dry wood substance in the same temperature range. On the basis of the data obtained by measurement, he draws the conclusion that $\overline{c}_{pw}$, apart from depending on a change in temperature, also depends on the volume of water. The mathematical dependence of $\overline{c}_{pw}$ on the temperature and volume of water is shown in expression (6).

$$\{\overline{c}_{pw}\}_{kJ/kg\cdot°C} = 1.08 + 4.08\cdot10^{-3}\cdot\{u\}_{\%} + 2.53\cdot10^{-3}\cdot\{t\}_{°C} + 6.28\cdot10^{-5}\cdot\{u\}_{\%}\cdot\{t\}_{°C} \qquad (6)$$

where:
$\overline{c}_{pw}$ - mean specific heat capacity of wood fiber, kJ/kg·°C,
u - moisture content, %,
t - temperature, °C

Expression (6) served as a means to determine the $\overline{c}_{pw}$ with the wood moisture content between 0 % and 25 % in a temperature range of 0 °C to 100 °C. The obtained values can be seen in Figure (1).

Volbehr's research is tangible proof of the influence of the wood moisture content on the specific heat capacity of wood fibers.

Kanter (1957) determines the specific heat capacity of pine, oak and birch in a temperature range of - 40 °C to 100 °C, with the moisture content varying between 0 % and 130 % (Figure 2). This data leads to the conclusion that the specific heat capacity of wood depends on the temperature and moisture content, while the variations between different wood species were very small.

The dependence of c_{pw} on temperature is linear in a range of moisture content from 5 % to 30 %, but for temperatures below 0 °C this dependence is broken into two lines with a different slope coefficient. This change in slope coefficients occurs at the temperature at which change in the phase of bound water ends.

For wood moisture content higher than 30 %, the dependence of c_{pw} on temperature is also linear with a sudden rise at a temperature slightly lower than 0 °C. This sudden rise is due to a change in the phase of free

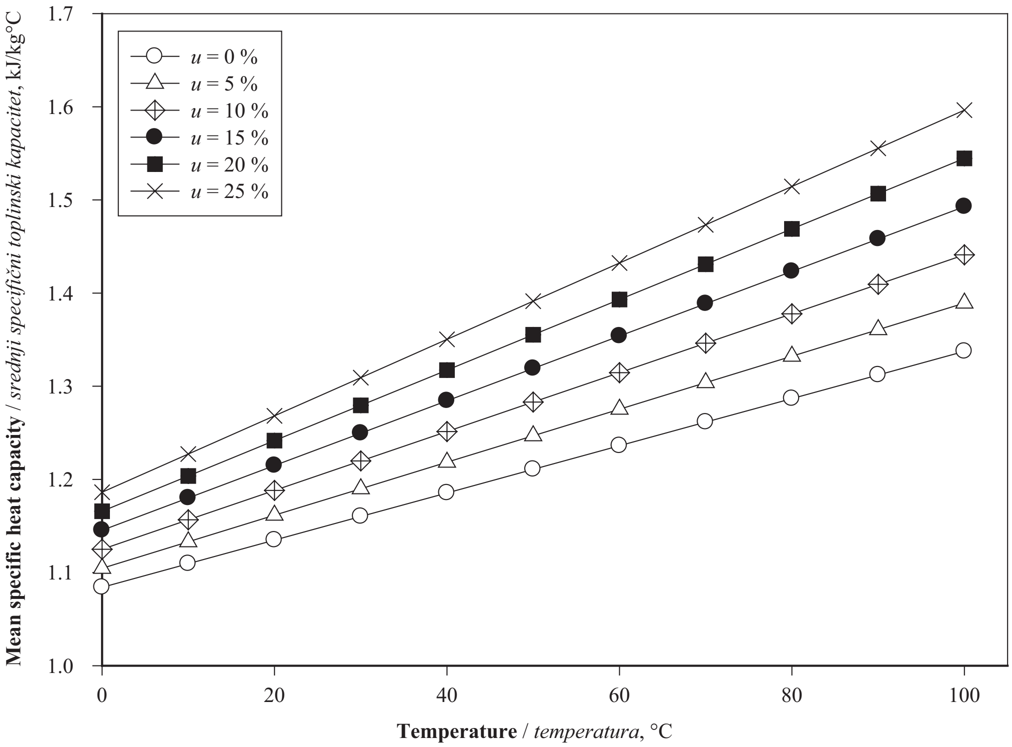

Figure 1 Dependence of specific heat capacity of wood fibers ($\overline{c}_{pw}$) on temperature with wood moisture content between 0 % and 25 %

Slika 1. Ovisnost specifičnoga toplinskog kapaciteta drvnih vlakanaca ($\overline{c}_{pw}$) o temperaturi za sadržaj vode od 0 do 25 %

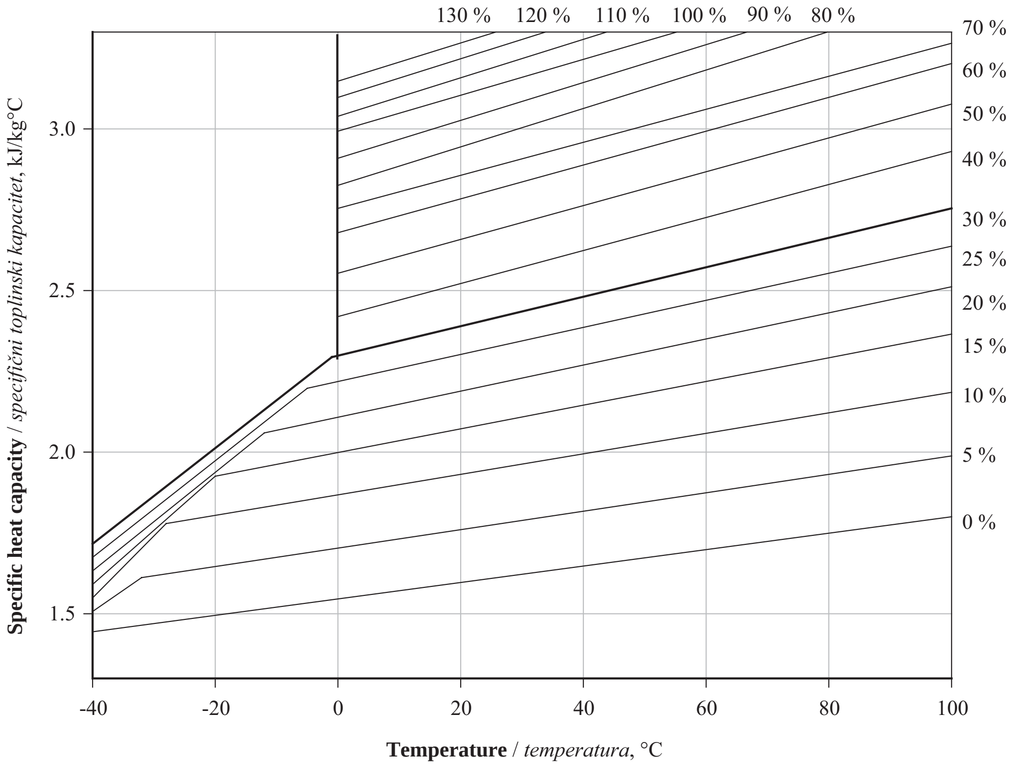

Figure 2 Dependence of specific heat capacity of wood on temperature (Kanter, 1957) and wood moisture content between 0 % and 130 %
Slika 2. Ovisnost specifičnoga toplinskog kapaciteta drva o temperaturi (Kanter, 1957.) za sadržaj vode od 0 do 130 %

water. At this point, there is also the change in the slope coefficient of the line.

Kuhlman (1962) determines the specific heat capacity of spruce, oak and beech wood in a temperature range of - 60 °C to 80 °C, with the moisture content below 30 %, by means of two different methods (the Esdorn – Kirsher method and the ice calorimeter method). Contrary to Kanter (1957), there were no significant changes in the specific heat capacity due to a change in the phase of bound water. The obtained values are considerably lower than those obtained by Kanter, but they coincide closely with the values obtained by the other authors at temperatures higher than 0 °C. Table 2 shows the average deviations of the available results of the other authors from Kanter's results.

Most of the authors arrive at the conclusion that the specific heat capacity of wood depends on the temperature and moisture content, while variations between wood species are very small. The available literature provides only two papers that mention greater variations between wood species. Narayanamurti *et al.* (1958) measured the specific heat capacity of nine Indian wood species (probably at room temperature), and the results cover the interval of (1.29 to 1.73) kJ/kg·°C. Koch (1969) published the results on the specific heat capacity

Table 2 The average deviations of the results of the other authors from Kanter's results for temperatures lower and higher than 0 °C and moisture content below and above 30 % (The USDA forest service general technical report FPL9, 1977)
Tablica 2. Srednja odstupanja rezultata ostalih autora od Kanterovih rezultata za temperature manje i veće od 0 °C te za sadržaj vode manji i veći od 30 % (USDA forest service general technical report FPL9, 1977.)

Author / *Autor*	**Mean deviation** / *Srednje odstupanje, %*			
	$t < 0$ °C		$t > 0$ °C	
	$u \leq 30$ %	$u > 30$ %	$u \leq 30$ %	$u > 30$ %
Chudinov (1968)	+ 6	+ 6	NA	NA
Chudinov, Stepanov (1971)	+ 14	+ 21	NA	NA
Dunlop (1912)	NA	NA	-19	NA
Emchenko (1958)	NA	NA	-15	NA
Hearmon, Burcham (1955)	NA	NA	-13	NA
Kanter (1957)	-	-	-	-
Koch (1969)	NA	NA	-18	NA
Komissarov (1969)	+ 1	+ 1	+ 1	+ 1
Kuhlmann (1962)	-20	NA	-17	NA
McMillin (1969)	NA	NA	-18	NA
Volbehr (1896)	NA	NA	-28	NA

of earlywood and latewood, as well as of hardwoods and softwoods. The results also suggest the possibility of variations between different types of wood.

Theoretical research into the specific heat capacity of wood was also directed at establishing a model of heat diffusion in the wood. A model that provides a satisfactory description of the change in the specific heat capacity with the change in the temperature and moisture content is obtained by solving the Fourier–Kirchhoff equation (Deliiski, 2012).

2 DISCUSSION
2. RASPRAVA

Due to the difference in results obtained by many authors, a comparison was drawn between the theoretical research conducted by Deliiski (2012) (DEL) and the research mentioned in the Wood Handbook (1999) (WH) and the Wood Technology Handbook (1967) (DIP). The temperature interval selected for the comparison was between 10 °C and 100 °C, and it results from a cross section of temperature intervals found in the literature. By means of equations from the studied literature, the specific heat capacity of wood was determined for a moisture content below the fiber saturation point (Figure 3) and for a moisture content above the fiber saturation point (Figure 4). It was assumed that the fiber saturation point corresponds to 25 % moisture content. Figures 3 and 4 clearly show that the research confirmed a linear dependence of the specific heat capacity of wood on temperature in the given temperature interval. The linearity is only disturbed in the Deliiski equation, but the term disturbing the linearity is very small; it equals $\frac{0,02}{\{u\}_{\%}+100}$, the order of magnitude of which is 10^{-4}. It should be noted that the results of the research mentioned in DIP cite the same equation of dependence of specific heat capacity on temperature, independent of the fiber saturation point. The equation of dependence of specific heat capacity on temperature in the research mentioned in the Wood Handbook is true in a temperature range of 7 °C to 147 °C, but the equation contains a linear dependence of c_{p0} on temperature, which, according to Dunlop's research, is linear in a temperature range of 0 °C to 100 °C.

By means of equation (5), the expression for the specific heat capacity was determined in a temperature range of 10 °C to 100 °C. The obtained average values are represented by equations (7), (8) and (9) for a moisture content below the fiber saturation point, and by equations (10), (11) and (12) for a moisture content above the fiber saturation point. Using the above equations, the average values of specific heat capacity were obtained for a moisture content between 0 % and 20 % (Figure 5) and for a moisture content between 80 % and 100 % (Figure 6). It is assumed that the fiber saturation point corresponds to 25 % wood moisture content.

$$\left\{\bar{c}_{\mathrm{pw(WH)}}\right\}_{\mathrm{kJ/kg\cdot°C}}=\frac{0.1031+0.0419\cdot\{u\}_{\%}}{1+0.01\cdot\{u\}_{\%}}+\frac{1.268}{1+0.01\cdot\{u\}_{\%}}-6.191\cdot10^{-2}\cdot\{u\}_{\%}-1.33\cdot10^{-4}\cdot\{u^2\}_{\%}+0.0774\cdot\{u\}_{\%} \quad (7)$$

$$\left\{\bar{c}_{\mathrm{pw(DEL)}}\right\}_{\mathrm{J/kg\cdot°C}}=\frac{2097\cdot\{u\}_{\%}+82600}{\{u\}_{\%}+100}+\frac{9.92\cdot\{u\}_{\%}+255}{\{u\}_{\%}+100}\cdot\frac{\{T_1\}_{\mathrm{K}}+\{T_0\}_{\mathrm{K}}}{2}+\frac{0.02}{\{u\}_{\%}+100}\cdot\frac{\{T_1^3\}_{\mathrm{K}}-\{T_0^3\}_{\mathrm{K}}}{3} \quad (8)$$

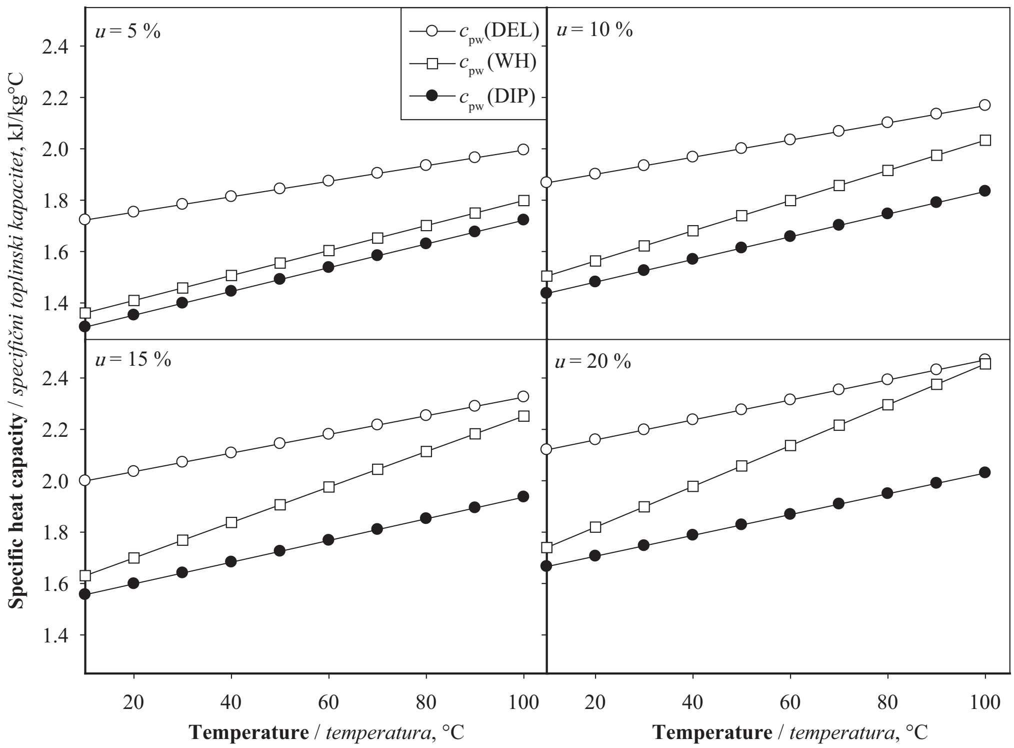

Figure 3 Dependence of specific heat capacity on temperature for a moisture content between 5 % and 20 %, according to DEL, WH and DIP
Slika 3. Ovisnost specifičnoga toplinskog kapaciteta o temperaturi prema DEL-u, WH-u i DIP-u za sadržaj vode od 5 do 20 %

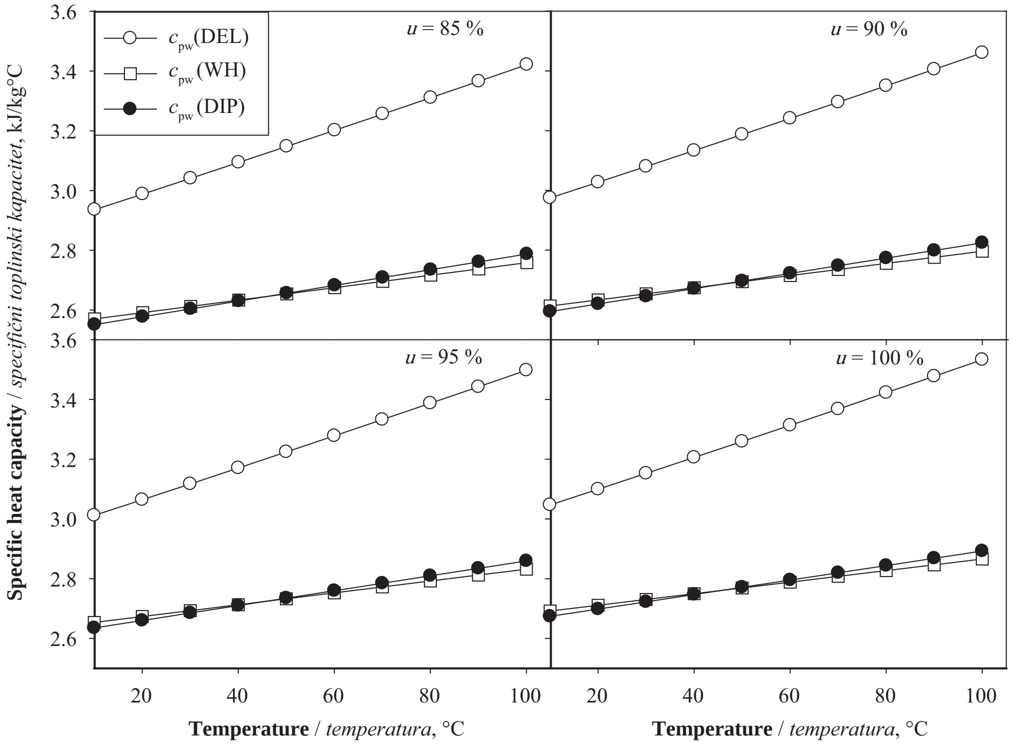

Figure 4 Dependence of specific heat capacity on temperature for a moisture content between 80 % and 100 %, according to DEL, WH and DIP
Slika 4. Ovisnost specifičnoga toplinskog kapaciteta o temperaturi prema DEL-u, WH-u i DIP-u za sadržaj vode od 80 do 100 %

$$\{\bar{c}_{\text{pw(DIP)}}\}_{\text{kJ/kg}\cdot°\text{C}} = \left(1 - \frac{100}{100 + \{u\}_{\%}} + \frac{26.6}{100 + \{u\}_{\%}} + \frac{0.116}{100 + \{u\}_{\%}} \cdot \frac{\{t_1\}_{°\text{C}} + \{t_0\}_{°\text{C}}}{2}\right) \cdot 4.186 \tag{9}$$

$$\{\bar{c}_{\text{pw(WH)}}\}_{\text{kJ/kg}\cdot°\text{C}} = \frac{0.1031 + 0.0419 \cdot \{u\}_{\%}}{1 + 0.01 \cdot \{u\}_{\%}} + \frac{1.268}{1 + 0.01 \cdot \{u\}_{\%}} \tag{10}$$

$$\{\bar{c}_{\text{pw(DEL)}}\}_{\text{J/kg}\cdot°\text{C}} = \frac{2862 \cdot \{u\}_{\%} + 55500}{\{u\}_{\%} + 100} + \frac{5.49 \cdot \{u\}_{\%} + 295}{\{u\}_{\%} + 100} \cdot \frac{\{T_1\}_{\text{K}} + \{T_0\}_{\text{K}}}{2} + \frac{0.36}{\{u\}_{\%} + 100} \cdot \frac{\{T_1^3\}_{\text{K}} - \{T_0^3\}_{\text{K}}}{3} \tag{11}$$

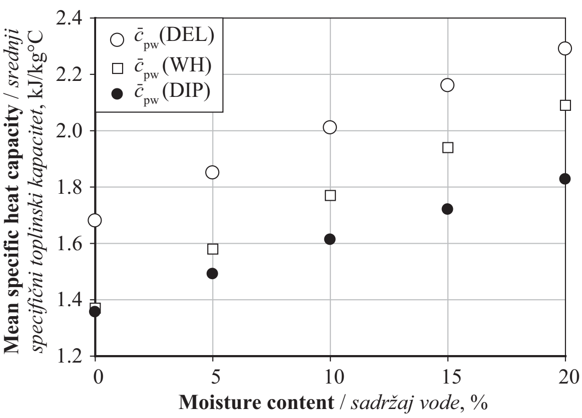

Figure 5 Dependence of the average specific heat capacity on moisture content for temperature ranging between 10 °C and 100 °C ($u < u_{fsp}$)
Slika 5. Ovisnost srednjeg specifičnoga toplinskog kapaciteta o sadržaju vlage za temperaturni interval od 10 do 100 °C; sadržaj vode je manji od točke zasićenja vlakanaca

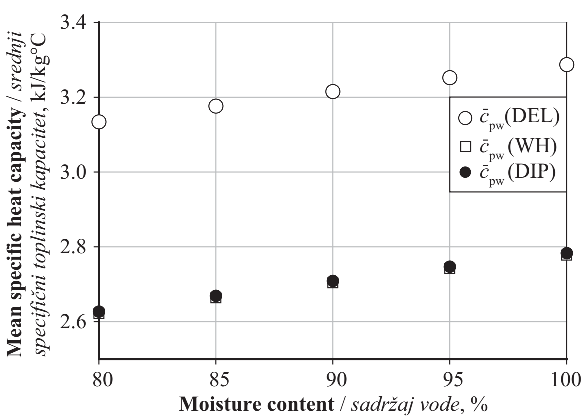

Figure 6 Dependence of the average specific heat capacity on wood moisture content for temperature ranging between 10 °C and 100 °C ($u > u_{fsp}$)
Slika 6. Ovisnost srednjega specifičnog toplinskog kapaciteta o sadržaju vode za temperaturni interval od 10 do 100 °C; sadržaj vode je veći od točke zasićenja vlakanaca

$$\{\bar{c}_{pw(DIP)}\}_{kJ/kg\cdot°C} = (1 - \frac{100}{100+\{u\}_{\%}} + \frac{26.6}{100+\{u\}_{\%}} + \frac{0.116}{100+\{u\}_{\%}} \cdot \frac{\{t_1\}_{°C} + \{t_0\}_{°C}}{2}) \cdot 4.186 \quad (12)$$

where:
$\bar{c}_{pw(WH)}$- mean specific heat capacity of wood (Wood Handbook),
$\bar{c}_{pw(DEL)}$ - mean specific heat capacity of wood (Deliiski),
$\bar{c}_{pw(DIP)}$ - mean specific heat capacity of wood (DIP),
u - moisture content,
T - temperature,
t - temperature.

3 CONCLUSION
3. ZAKLJUČAK

The present analysis leads to the conclusion that the differences in the results obtained by different authors are significant. Most of the authors conclude that specific heat capacity depends on the temperature and wood moisture content, while variations between different wood species are very small. Regarding the discrepancy in the results obtained from different sources, future research should determine the specific heat capacity of several different species of wood, in the same temperature range and the same range of moisture content. The measurements should be made by standardized methods for measuring specific heat capacity, in order to obtain reliable results with the lowest possible measurement uncertainty. Thus obtained data for specific heat capacity can be used for testing the validity of the models suggested so far, as well as their validity and efficiency for industrial purposes.

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