THERMAL CONDUCTIVE PROPERTIES OF WOOD, GREEN OR DRY, FROM -40° TO +100° C: A LITERATURE REVIEW

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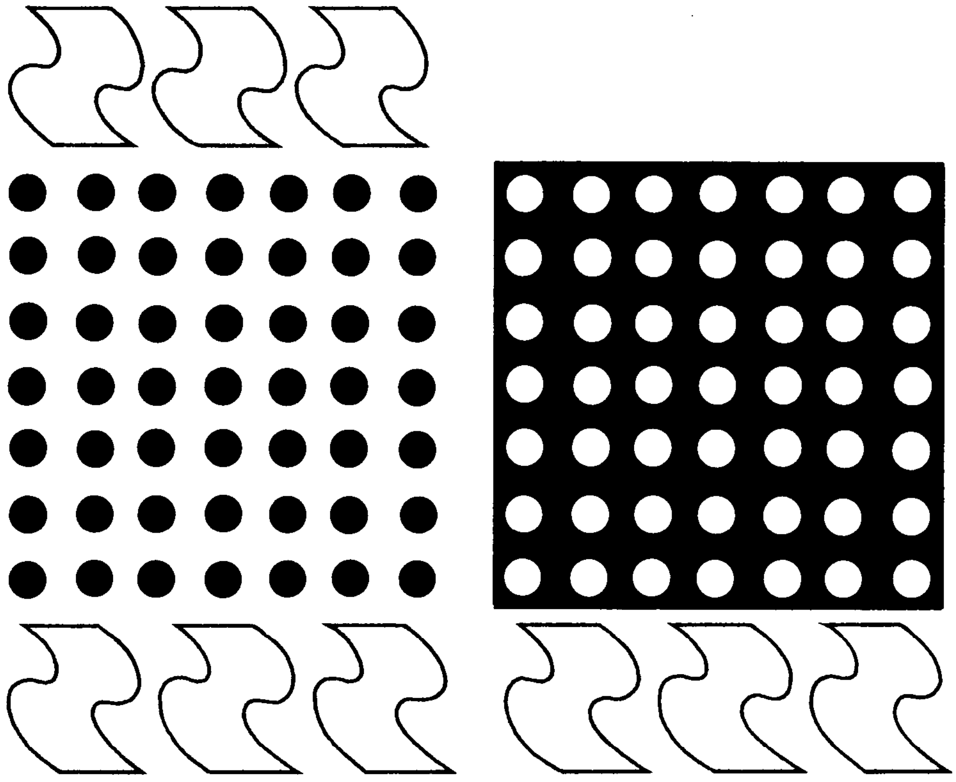

Summary

This literature review was conducted in connection with a study on heat transfer in frozen logs. A combination of data by two researchers on specific heat and thermal conductivity and diffusivity in the radial direction of wood, at various temperatures and moisture contents, is discussed and compared with data from other sources. Limited information found for the tangential and longitudinal directions is also included in the report. In addition, a data set of average thermal diffusivities in the radial direction of wood is provided for temperature intervals involving complete thawing.

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THERMAL CONDUCTIVE PROPERTIES OF WOOD, GREEN OR DRY, FROM -40° TO +100° C: A LITERATURE REVIEW

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Introduction

Three important thermal conductive properties are specific heat, thermal conductivity, and thermal diffusivity. Specific heat, or more correctly the specific heat capacity of a material, is the thermal energy required to produce one unit change of temperature in one unit of mass. Thermal conductivity is a measure of the rate of heat flow through a material subjected to a temperature gradient. Thermal diffusivity is a measure of how quickly a material can absorb heat from its surroundings (USDA Wood Handbook 1974). The relationship between these properties is given by:

$$\alpha = \frac{k}{c \cdot \rho}$$

where

α = thermal diffusivity,

k = thermal conductivity,

c = specific heat, and

ρ = density.

Data on specific heat, thermal conductivity, and thermal diffusivity of wood were collected from the literature in connection with a study on heat transfer in frozen logs. The range of interest was from -40° to +100° C for dry and moist wood of any species and for any anatomical direction.

A combination of data by Kanter (1957) and Chudinov (1968) provides the only system that covers the whole range of interest. For this reason, their system is used extensively here to form the basis for an overall comparison with values from other authors. Usually the data differ considerably from one author to another. Other data are not only fragmentary but often incomplete regarding temperature, moisture content, and anatomical direction. Such incomplete data are not included in this discussion. This report also contains a set of average thermal diffusivities by Chudinov (1968) for temperature intervals involving the thawing of wood.

All the suitable data were individually compared with the corresponding values from the data system by Kanter and Chudinov (1957 and 1968, respectively), and deviations were expressed in percent of these latter values. For comparing curves, sample values were taken to achieve uniform weighting of the whole temperature and moisture content range covered by the curves. The deviations were grouped by author and certain temperature/moisture categories, but only the arithmetic means of the groups are presented here to indicate discrepancies among data sources.

Specific Heat

Kanter (1957) recorded the specific heat, c, of wood over a range of -40° to + 100° C and 0 to 130 percent moisture content by deriving the data from his measured thermal conductivities and diffusivities (fig. 1). Unfortunately, no data points are given. Specific heat hardly varied with wood species (pine, oak, birch).

Similar results were reported by Chudinov (1968) and Komissarov (1969) for smaller temperature ranges. Chudinov and Stepanov (1971), using an adiabatic calorimeter, determined significantly larger specific heat values for larch below 0° C. Kuhlmann (1962) with the quasi-steady-state

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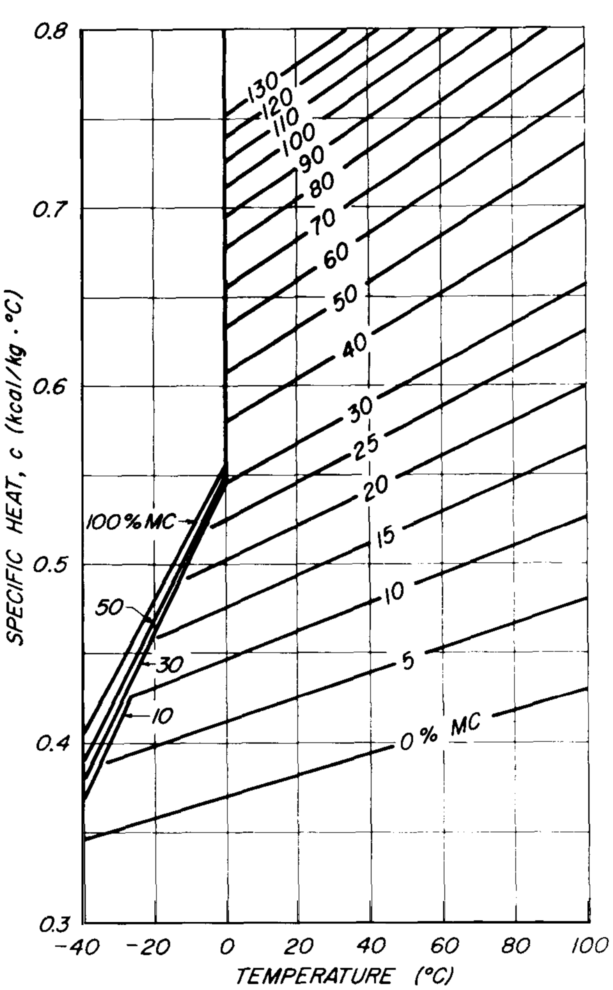

Figure 1.--Specific heat, c, versus temperature, with moisture content as the parameter.

From Kanter (1957)

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apparatus developed by Krischer and Esdorn and with an ice calorimeter, measured the specific heat of spruce, oak, and beech at temperatures between -60° and +80° C and moisture contents below 30 percent (fig. 2). Contrary to Kanter, Kuhlmann did not suggest a noticeable effect of phase change in hygroscopic moisture. Similarly, other researchers (Kubler 1962, Chudinov 1968, Noack and Geissen 1976) found evidence that bound water undergoes only a limited phase change which occurs over a large temperature range. Kuhlmann's values are also considerably lower than Kanter's at almost all levels but are in good agreement with some other sources (all limited to temperatures above 0° C, however), as was discussed previously by Beall (1968) and Skaar (1972). Free water in wood seems to freeze at a temperature slightly below 0° C, usually somewhere between -0.1° and -2° C, depending on the concentration of sugars dissolved in the water (Kubler and Traber 1964, Chudinov 1968). Thermal properties of wood that contains free water are discontinuous at this temperature due to the difference in thermal properties of liquid water and ice.

A relative comparison of specific heat data among various sources, with Kanter's (1957) data as a basis, is given in table 1. It should be kept in mind that occasionally there is a considerable difference between individual and mean deviations of one author's data from the data by Kanter, particularly for very low temperatures.

Thermal Conductivity

Radial

Kanter (1957) plotted the thermal conductivity in the radial direction of birch wood, k_{rb}, over a range of -40° to +100° C and 0 to 130 percent moisture content (fig. 3). No data points are given. His experimental data resulted from use of an instantaneous heat source. Chudinov (1968) presented practically the same values over a shorter temperature range, and he proposed an adjustment factor, A,, for each different specific gravity (fig. 4). For temperatures around 25° C, the rate of the suggested linear increase in thermal conductivity with specific gravity agrees well with other sources (Rowley 1933, Wangaard 1940, MacLean 1941, Kuhlmann 1962). Values at other temperatures are not available for comparison.

Provided that the wood species itself has no important effect on thermal conductivity, data from other sources for almost any species of known specific gravity can then be compared with the appropriate values of $k_{rb} \cdot A_k$ by Kanter and Chudinov. Only Komissarov (1969) provided larger or approximately equal values, whereas the data by Kuhlmann (1962), by Sova et al. (1970) by Chudinov and Stepanov (1971) and the values listed in the review by Ratcliffe (1964) are usually much smaller than the data by Kanter and Chudinov (1957 and 1968, respectively). Komissarov's study dealt with larch at -20° to +20° C and 0 to 90 percent moisture content. Kuhlmann investigated spruce, oak, and beech with the Krischer and Esdorn apparatus, over a range of -60° to +80° C and 0 to 30 percent moisture content. Sova et al. studied maple at 15° to 30° C and 0 to 100 percent moisture content, using Bock's steady-state apparatus. Chudinov and Stepanov employed a non-steady-state heating device with constant heat flux in their investigations of larch below 0° C and up to 80 percent moisture content.

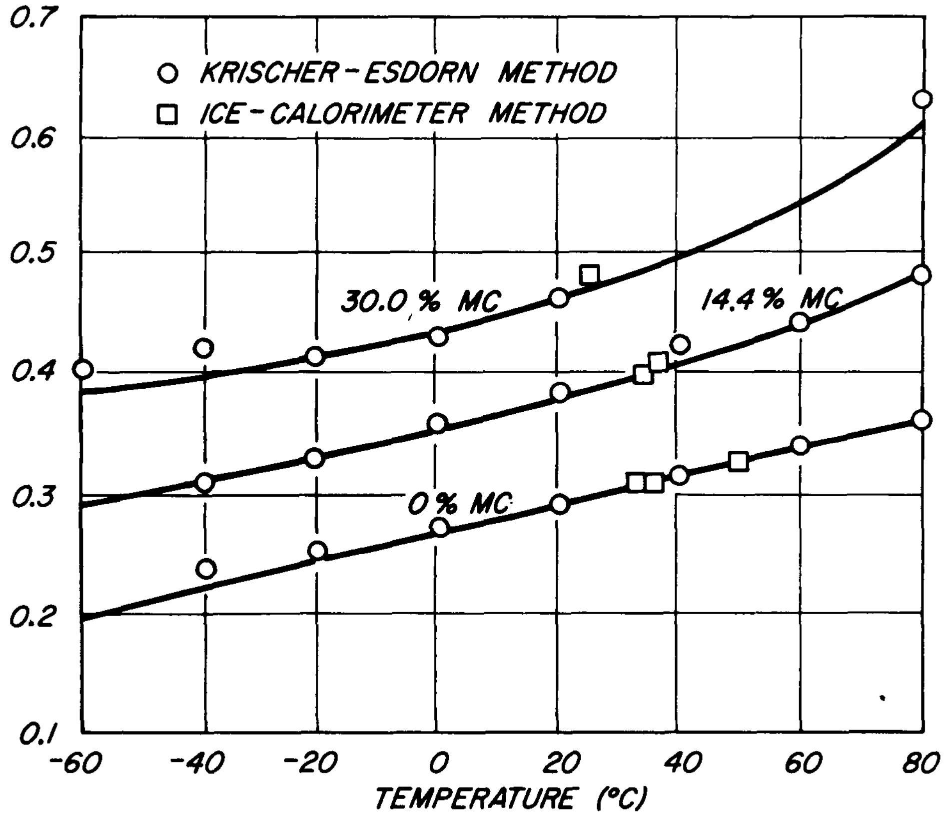

Figure 2.--Specific heat, c, versus temperature, with moisture content as the parameter.

From Kuhlmann (1962)

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Table 1. -- Mean deviations of specific heat data by various authors from the data by Kanter (1957)

Source	Mean deviations, percent			
	<0° C		>0° C	
	≤30% MC	>30% MC	≤30% MC	>30 % MC
Chudinov (1968)	+6	+6		
Chudinov, Stepanov (1971)	+14	+21		
Dunlap (1912) 0% MC			-19	
Emchenko (1958)			-15	
Hearmon, Burcham (1955)			-13	
Kanter (1957)	--	--	--	--
Koch (1969) 0% MC			-18	
Komissarov (1969)	+1	+1	+1	+1
Kuhlmann (1962)	-20		-17	
McMillin (1969) 0% MC			-18	
Volbehr (1896)			-28	

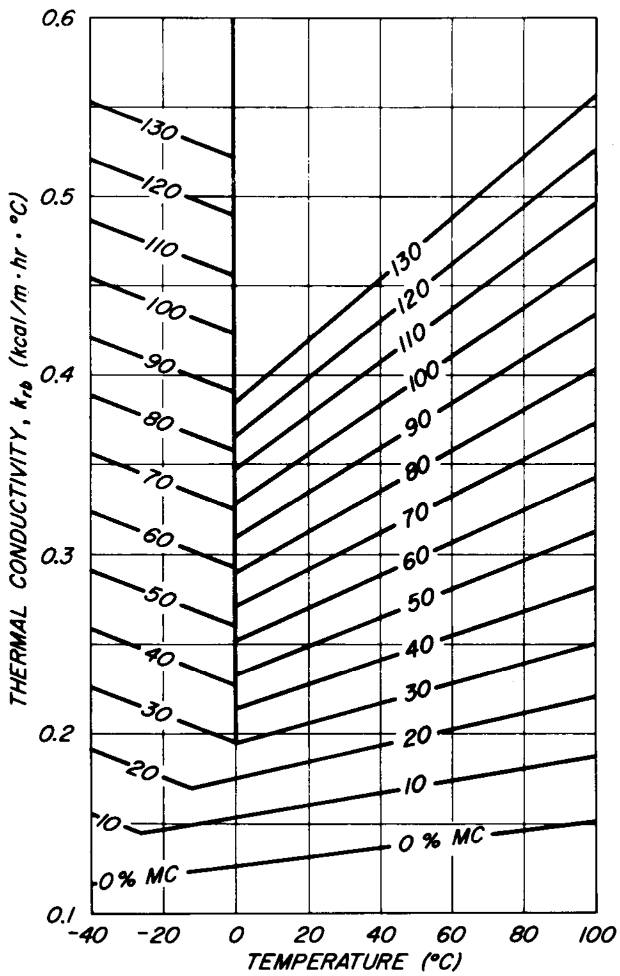

Figure 3.--Thermal conductivity in the radial direction of birch wood, k_{rb}, versus temperature, with moisture content as the parameter. Specific gravity (ovendry mass, green volume basis) is 0.515.

From Kanter (1957)

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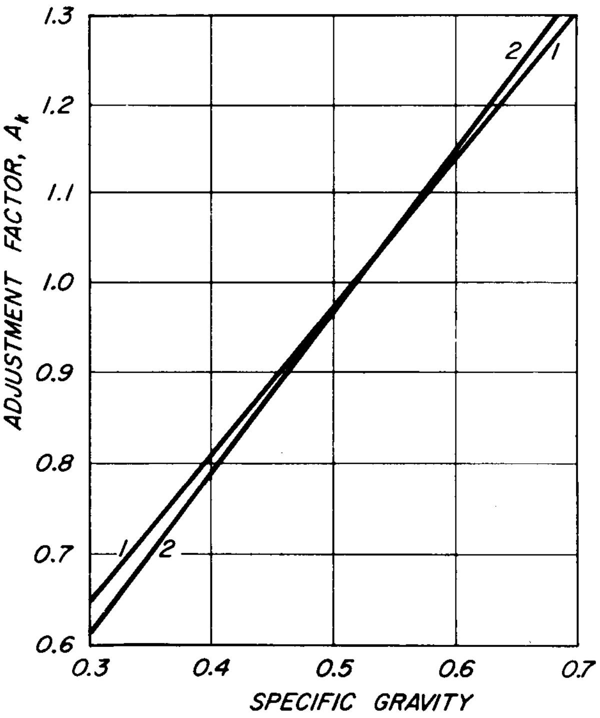

Figure 4.--Adjustment factor, A_k, versus specific gravity (ovendry mass, green volume basis) for use in connection with the conductivities of figure 3. Line 1 is valid for moisture contents <40%, line 2 for moisture contents >40%.

From Chudinov (1968)

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These comparisons are summarized in table 2 with Kanter's and Chudinov's (1957 and 1968, respectively) comprehensive data system used as a basis. Some individual deviations differ substantially from the mean deviations listed in the table, especially at low temperatures.

Tangential

Tangential thermal conductivity of wood is usually somewhat smaller than radial conductivity. Griffiths and Kaye (1923) found tangential conductivity to be 0.9 to 0.95 times the radial conductivity in three hardwoods and one softwood, whereas Wangaard (1940) and Kuhlmann (1962) observed such clear distinction only in hardwoods. Kuhlmann suggested a strong effect of the rays: Oak, with a large number of ray cells, exhibited a large difference between tangential and radial conductivity, while the difference was small in spruce, which has fewer ray cells. Chudinov (1968) suggested a proportionality factor of 0.97 for softwood containing relatively little (10 pct) latewood and 0.87 when there is much (40 pct) latewood.

It thus appears that the ratio of tangential versus radial conductivity is primarily determined by the ray cell volume in hardwoods and by the latewood volume in softwoods.

Longitudinal

Thermal conductivity along the grain is significantly greater than across the grain. According to Griffiths and Kaye (1923), the ratio of longitudinal versus radial conductivity at 20° C is about 1.75 for ash, 1.85 for mahogany and spruce, and 2.25 for walnut, all air-dry. Komissarov (1969) observed a comparable value of 1.5 for larch at 30 percent

Table 2. -- Mean deviations of thermal conductivity data by various authors from the data $k_{rb} \cdot A_k$ by Kanter and Chudinov (1957 and 1968, respectively)

Source	Mean deviations, percent			
	<0° C		>0° C	
	≤30% MC	>30% MC	≤30% MC	>30% MC
Chudinov (1968) 1 species	0	0		
Chudinov, Stepanov (1971) 1 species	-31	-2		
Griffiths, Kaye (1923) 5 species			-24	
I.H.V.E. London (1959) 4 species			-23	
Kanter (1957) 1 species	--	--	--	--
Komissarov (1969) 1 species	+13	+6	+11	0
Kuhlmann (1962) 3 species	-22		-19	
MacLean (1941) 30 species[1]			-15	-7
Rowley (1933) 22 species[1]			-23	
Sova et al. (1970) 1 species			-15	-24
Wangaard (1940) 34 species			-19	

[1] No distinction was made between the radial and the tangential direction of wood.

moisture content and 20° C. Sova et al. (1970) reported a ratio of 2.2 for maple at 20 percent moisture content and 20° C, but of 2.0 at 100 percent moisture content. Kanter (1957) determined a value of 2.05 for ovendry pine at 20° C; when the moisture content was 140 percent, the value was only 1.8. MacLean (1941) found longitudinal conductivity to be about 2.25 to 2.75 times the radial or tangential conductivity in Douglas-fir and red oak, with 6 to 15 percent moisture content and at an average temperature of 30° C.

Thermal Diffusivity

Radial

Kanter (1957) plotted thermal diffusivity in the radial direction of birch wood α_{rb}, from -40° to +100° C and from 0 to 130 percent moisture content (fig. 5). Data points are lacking. His experiments were done with an instantaneous heat source. Chudinov (1968) derived similar values from specific heat and conductivity data, and he also proposed an adjustment factor, A, (fig. 6), for each different specific gravity. Its values are close to unity for specific gravities of 0.4 to 0.7. Maku (1954) and Kuhlmann (1962) found no significant effect of specific gravity over this range.

A comparison of diffusivity data by Maku (1954) and Kuhlmann (1962) with the values of $\alpha_{rb} \cdot A_{\alpha}$ by Kanter and Chudinov (1957 and 1968, respectively) shows fair overall agreement, but considerable individual deviations can also be observed. Kuhlmann derived his values from specific heat and thermal conductivity. Maku conducted heating experiments under nonsteady-state conditions with specified surface temperatures,

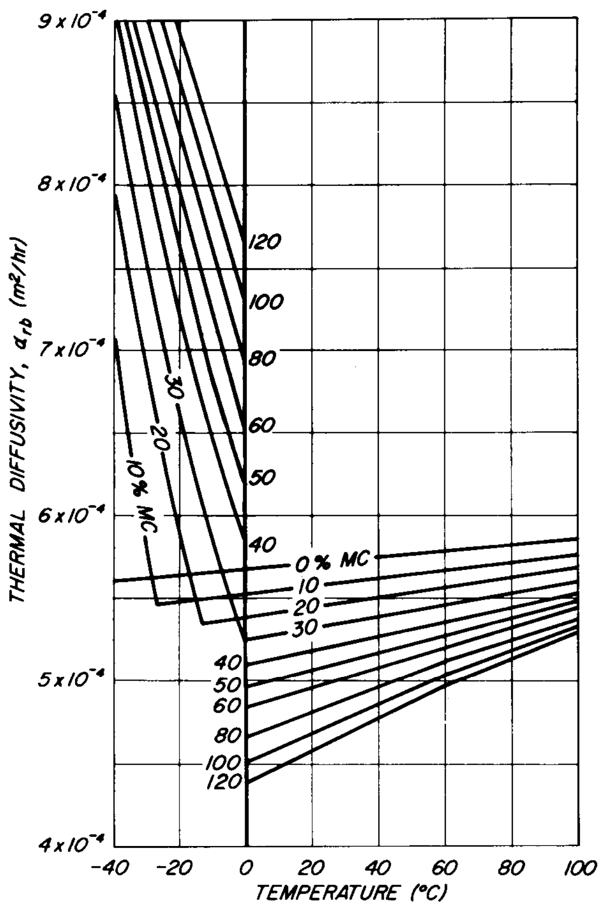

Figure 5.--Thermal diffusivity in the radial direction of birch wood, α_{rb}, versus temperature, with moisture content as the parameter. Specific gravity (ovendry mass, green volume basis) is 0.515.
From Kanter (1957)
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using slices of different wood species at varying moisture contents. MacLean (1930) analyzed data based on heating experiments with sections of green southern pine roundwood of different diameters. He found thermal diffusivity values considerably greater than those in the data by Kanter and Chudinov. Chudinov and Stepanov (1971) determined thermal diffusivities of larch below 0° C and up to 80 percent moisture content, employing a nonsteady-state heating device with constant heat flux. Their results are substantially lower than the values obtained by Kanter and Chudinov.

The largest discrepancies between the data of Kanter and Chudinov (1957 and 1968, respectively) and of other sources (table 3) were observed at very low temperatures.

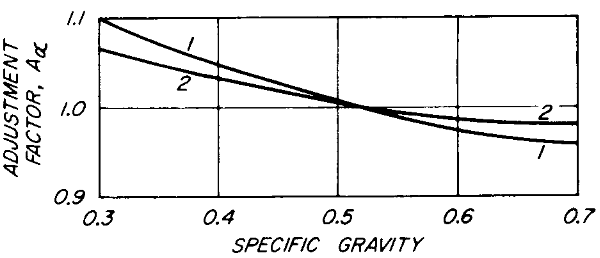

Figure 6.--Adjustment factor, A_α, versus specific gravity (ovendry mass, green volume basis) for use in connection with the diffusivities of figures 5 and 7. Line 1 is valid for moisture contents <40%, line 2 for moisture contents >40%.
From Chudinov (1968)
M 144 818

Tangential

As thermal diffusivity is proportional to thermal conductivity and as specific heat and density are independent of the anatomical direction, one can expect the ratio of tangential to radial diffusivity to be the same as of tangential to radial conductivity.

Longitudinal

The ratio of longitudinal to radial diffusivity should be equal to the ratio of longitudinal to radial conductivity. However, Maku (1954) in his heating experiments with various wood species found larger ratios than can be expected from the above, particularly at a low moisture content. For instance, at 20 percent moisture content and an average temperature of about 60° C, the ratio was between 4 and 5.5; at 90 percent moisture content and above, the ratio was about 2. Maku tries to explain this behavior by moisture movement downhill along the temperature gradient (Soret effect).

Average Diffusivity for Temperature Intervals Involving Thawing

Chudinov (1968) developed a set of average diffusivities in the radial direction of birch wood, $\alpha_{rb,avg}$, valid for given initial and final temperatures below and above 0° C, respectively, and constant moisture contents of up to 120 percent (fig. 7). A specific gravity adjustment factor, A_α (fig. 6) may be used for species other than birch. The peculiarity of this data set is that latent heat effects have been incorporated so that no further phase change allowance in the heat-conduction equation is necessary (Chudinov 1968). It must be empha-

Table 3. -- Mean deviations of thermal diffusivity data by various authors from the data $\alpha_{rb} \cdot A_{\alpha}$ by Kanter and Chudinov (1957 and 1968, respectively)

Source	Mean deviations, percent			
	<0° C		>0° C	
	≤30% MC	>30% MC	≤30% MC	>30% MC
Chudinov (1968)				
1 species	-6	-6		
Chudinov, Stepanov (1971)				
1 species	-39	-25		
Kanter (1957)				
1 species	--	--	--	--
Kuhlmann (1962)				
3 species	-2		-2	
MacLean (1930)				
1 species				+20
Maku (1954)				
13 species[1]			0	-11

[1] No distinction was made between the radial and the tangential direction of wood.

sized that this approach is only valid if the wood thaws completely.

Average diffusivity was computed as

$$\alpha_{rb,avg} = \frac{k_{rb,avg}}{c_{avg} \cdot \rho}$$

where

$k_{rb,avg}$ = average conductivity

c_{avg} = average specific heat.

Average conductivity was calculated from graphical integration of conductivities at constant temperatures (fig. 3) over any given temperature interval,

$$k_{rb,avg} = \frac{\int_{t_i}^{0^\circ C} k_{rb}(t)dt + \int_{0^\circ C}^{t_f} k_{rb}(t)dt}{t_f - t_i}$$

where

t_i = initial temperature below 0° C

t_f = final temperature above 0° C, averaged over the cross section of the piece.

Two-step integration was necessary because of discontinuity of the thermal properties at 0° C when the moisture content is greater than 30 percent.

Average specific heat was determined as

$$c_{avg} = \frac{\int_{t_i}^{0^\circ C} c^*(t)dt + \int_{0^\circ C}^{t_f} c(t)dt + \Delta H_f\left(\frac{MC - 30\%}{100\% + MC}\right)}{t_f - t_i}$$

where

MC= moisture content of wood (%, ovendry mass basis)

ΔH_f= latent heat of fusion of free water, i.e. 80 kcal/kg water.

Chudinov defines $\Delta H_f\left(\frac{MC - 30\%}{100\% + MC}\right)=0$ for MC < 30%. The c values used in the computations are apparently those of figure 1. The quantity c*, however, is the somewhat arbitrarily derived specific heat of frozen wood whose values are larger than Kanter's (and Chudinov's) values of c. Therefore, the average diffusivities of figure 7 are occasionally as much as 20 percent -- but often less than 10 percent -- smaller than those one can derive from Kanter's (1957) data.

Conclusions

The combined data by Kanter (1957) and Chudinov (1968) allow one to roughly estimate specific heat and thermal conductivity and diffusivity in the radial direction of almost any wood

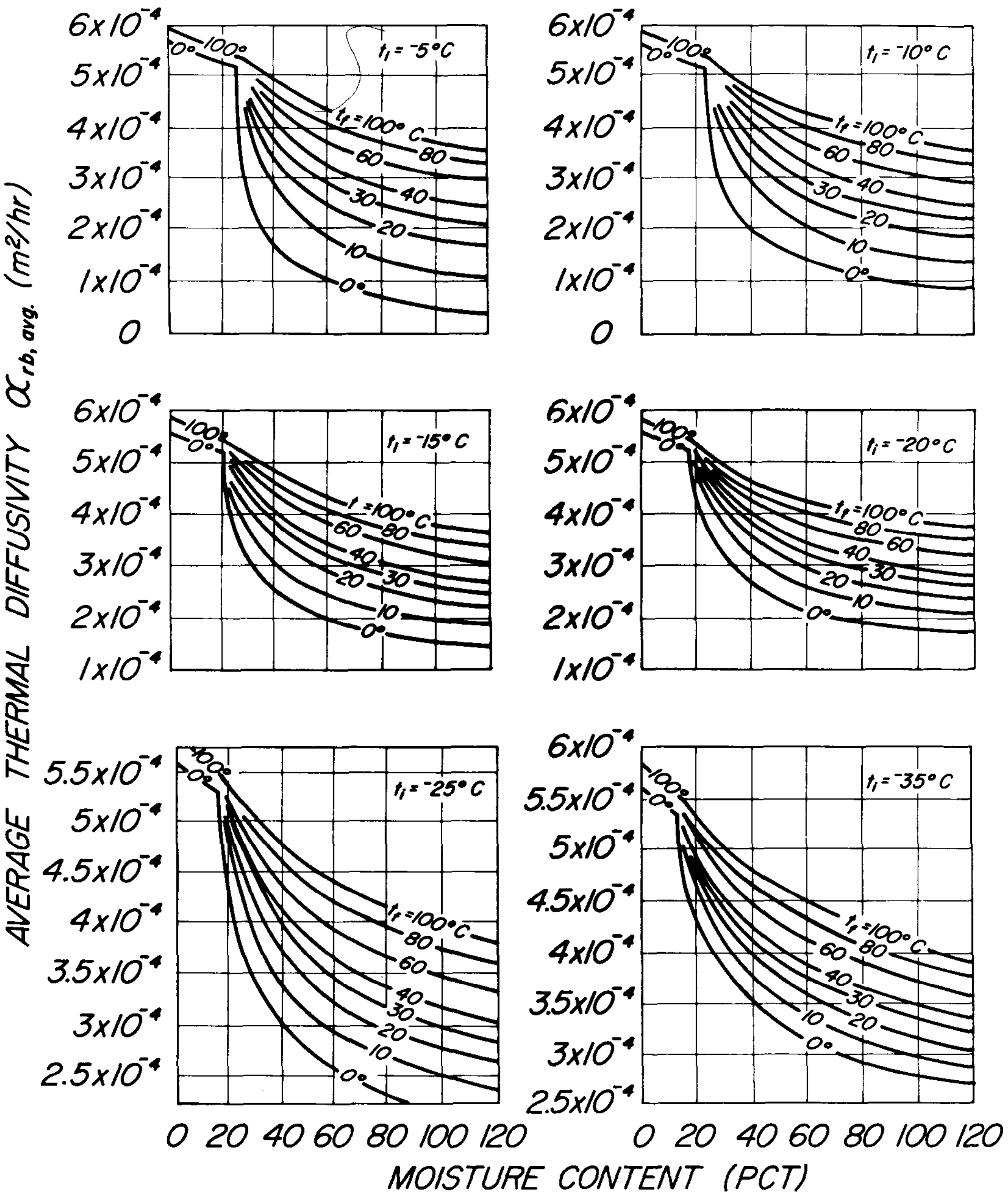

Figure 7.--Average thermal diffusivity in the radial direction of birch wood, $\alpha_{rb,avg}$, versus moisture content, with initial temperature t_i, and final temperature averaged over the cross section of the piece, t_f, as the two parameters. Specific gravity (ovendry mass, green volume basis) is 0.515.

From Chudinov (1968)

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species, at temperatures from -40° to +100° C and moisture contents of up to 130 percent. These values as compared with data by other sources are generally on the high side, with the largest discrepancies observed at very low temperatures. However, due to the lack of comparative values in a number of categories (particularly for moisture contents above 30 percent, at temperatures both above and below 0° C), no attempt was made to synthetize another data system.

Thermal conductivity and diffusivity in the tangential direction usually appear slightly smaller than in the radial direction. In the longitudinal direction, however, these properties are much larger but seem to vary considerably with species and moisture content, and possibly also with temperature. Research on longitudinal conductivity and diffusivity is needed, especially with frozen wood.

According to Chudinov (1968) heating times of frozen logs undergoing complete thawing can be estimated by direct application of his average thermal diffusivities to the heat-conduction equation. (These values apply only to one-dimensional heat transfer in the radial direction.) These data should be used with some caution.

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