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Effects of Moisture Content Difference and Temperature Variation on Thermal Conductivity for Coniferous and Broadleaf Species in Taiwan

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The study used different coniferous and broadleaf species, from domestic wood in Taiwan, as the specimens to determine the effect of various species on thermal conductivity (λ) at different densities. The environment changes of relative humidity (RH) in the moisture content (MC), and the influence of temperature variation on the λ of various species were investigated. The air–dried density of various species was in the range of 0.30 to 0.91 g/cm^3, and the λ ranges were from 0.1367 to 0.2270 W/mK. The higher the density, the faster the λ. In other words, the lower the density with a slower λ because of porosity of wood. The MC increased from 4.0 to 20.0%, the λ increased from 0.1090 to 0.1900 W/mK. The λ of wood increased with the increase of MC. The temperature increased from 50 to 90°C, the λ of various specimens increased from 0.1024 to 0.2411 W/mK. The λ of wood is affected by changes in density, MC, and temperature, and increases with increasing density, MC, and temperature. The temperature influenced on the λ of various species was greater than that on the MC increased by the change of RH inferentially. The MC of wood species with different densities under different RH, and the effects of λ at different temperatures of wood; therefore, can be used as a reference for subsequent evaluation of λ as the domestic woods are used in interior materials in Taiwan.

Key words: Domestic Wood in Taiwan, Density, Moisture Content (MC), Temperature, Thermal Conductivity (λ)

INTRODUCTION

Taiwan is located in the subtropical zone, and the overall environment has high temperature and relative humidity (RH) due to monsoons and an island climate. As weather change is more severe due to global warming in recent years, reducing the temperature variation of indoor living environment is one of the important topics at present in Taiwan. The wood can be used as interior decoration material due to particular textures and characteristics, warming the cold interior space, and hygroscopic and dehumidification. It can regulate the temperature and humidity inside residential buildings (Siau, 1984). These assistances reduce the power consumption of dehumidifiers, air conditioning, and heating. Wood is used as an interior decoration material for buildings. With air conditioning, the building with wood has a lower RH difference. When there is a temperature gradient inside the wood, the heat energy is transferred from high to low temperature, known as thermal conduction (Harada *et al*., 1988). The thermal conductivity (λ) measures the flow velocity of heat inside the material. When the temperature difference between both sides of thickness per unit area is 1°C, it is represented by the heat flow in unit time, and the unit is kcal/mh°C (W/mK) (MacLean, 1941; Peron *et al*., 2011; Yu *et al*., 2011). A higher λ represents a faster thermal transfer rate (Kandem *et al*., 2002).

Wood is a porous material. Its porosity can influence the thermal property of wood. It can regulate the temperature in the natural environment (Viitaniemi, 1997). Regarding temperature, the temperature coefficient of wood density of 0.30 g/cm^3 is 0.0800/°C, and that of 0.50 g/cm^3 is 0.0605/°C. The wood is unlikely to conduct heat for low λ, and can insulate heat (Kollmann and Wilfred, 1967). Generally, the λ of water at 20°C is 0.5000 kcal/mh°C (0.5815 W/mK). For example, the moisture content (MC) in the broadleaf species–*Swietenla macropnylla* is 13%, and the MC in coniferous species–*Abies kawakamii* is 10%. In air–dried conditions, the longitudinal λ of the MC in the broadleaf species–*Abies kawakamii* and the MC in coniferous species–*Abies kawakamii* is 0.2700 and 0.1700 kcal/mh°C (0.3140 and 0.1977 W/mK), and the transverse value is 0.1300 and 0.1100 kcal/mh°C (0.1512 and 0.1279 W/mK), respectively. The λ increases with MC. Therefore, the wood density, temperature, and MC are the major factors that influence wood thermal conduction (Steinhagen, 1977; Tenwolde *et al*., 1988; Unsal *et al*., 2003).

Generally, the λ of air is 0.0210 kcal/mh°C (0.0244 W/mK), and the λ of water is as 0.5040 kcal/mh°C (0.5862 W/mK), which is about 24 times of the air. A higher the MC in the wood has the lower the air content and the larger λ. As the wood density is a factor which influences λ, the higher the density is, the larger (faster) is the λ. According to the comparison between the *Cunninghamia lanceolata* and *Larix gmelinii* of coniferous species, and that between the *Quercus* spp. and *Ulmus pumila* of broadleaf species, the absolute-dried density and porosity of the *Cunninghamia lan-*

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ceolata of coniferous species are 0.34 and 0.77, and that of *Larix gmelinii* are 0.51 and 0.66, respectively. The absolute–dried density and porosity of *Quercus* spp. of broadleaf species are 0.76 and 0.49, and that of *Ulmus pumila* are 0.60 and 0.60, respectively. The broadleaf species has a larger λ as the coniferous species has a higher porosity than the broadleaf species (Peron et.al., 2020).

This study aimed to investigate the influence of different temperatures and MCs on the λ of various coniferous and broadleaf species in Taiwan at different densities to determine λ with different air–dried densities. The specimens were placed in environments with different RH to evaluate the effect of the MC difference on λ. The specimens were placed in different temperatures to determine the λ difference. The result is expected to be a reference for subsequent research on the thermal conduction of various species as interior decoration materials in Taiwan.

MATERIALS ANDMETHODS

Experimental materials

This study employed three kinds of coniferous species from Chiayi Fenchi Lake, the 141st Forest Compartment of Chiayi Forest District Office, Taiwan. Three sorts of coniferous species: *Cunninghamia lanceolate*, *Chamaecyparis formosensis*, and *Cryptomeria japonica* (Forest Bureau, 2016). In addition, eight kinds of broadleaf species from 3 K+250 M of Shuanglong Forest Road under the Nantou Forest District Office were provided by the 59th Forest Compartment of Luanda Working Circle. Eight kinds of broadleaf species: *Paulownia kawakamii*, *Melia azedarach*, *Macaranga tanarius*, *Machilus zuihensis*, *Swietenia macropnylla*, *Pasania ternaticupula*, *Laurocerasus phaeosticta*, and *Zelkova serrata*.

Test methods

Preparation of specimens

The thickness of 11 specimens at different densities was determined using a band–sawing machine and planer. The width was sawn by a slitter, and the exact size was cut by a circular sawing machine. Sound wood was selected as the specimens, and the wide belt sander was used for surface sanding. The specimen size was 120×70×15 mm, and there were 40 pieces per assortment. These specimens were placed for conditioning at a temperature of 20°C and 65% RH until the moisture content was homogenized for future use.

Determination of basic properties

The moisture content (MC, %) of specimens of coniferous and broadleaf species was determined according to CNS 452 (2013) Wood – Determination of moisture content for physical and mechanical test. The air–dried density (g/cm^3) of them was determined according to CNS 451 (2013) Wood – Determination of density for physical and mechanical tests.

Determination of thermal conduction

A portable Heat Flow Meters produced by Kyoto Electronics Manufacturing was used for measuring thermal conduction. After the induction piece of the Heat Flow Meters was placed in the center of specimen, the induction piece was fastened on the wood surface by a clamp to measure the real–time thermal flux density and temperature of the specimen surface, and to determine the thermal flux density, and the surface temperature of each specimen.

The thermal conductivity is calculated as:

Thermal conductivity (λ, W/mK) = (q·S) / (AtΔT) = (Q·S) / (ΔT)

Where q is the heat energy of specimen; S is the thickness of specimen (m); A is the surface area (m^2); t is the time per unit (second, s); ΔT is (θ_2–θ_1), and Q is the thermal flux density (W/m^2)

Thermal conductivity (kcal/mh°C) × 1.163 = thermal conductivity (W/mK) (Steinhagen, 1977; Takegoshi *et al*., 1982; Tenwolde *et al*., 1988; Yu *et al*., 2011; Peron *et al*., 2020)

Where W represents the energy consumed per unit time of specimen (W); m represents the thickness of specimen (m), and K represents the absolute temperature (K)

Determination of MC difference and λ

Three medicaments were used: potassium carbonate (K_2CO_3) 43% RH, sodium chloride (NaCl) 75% RH, and barium chloride ($BaCl_2$) 90% RH. They were mixed to form a saturated solution, and put in a sealing box. The red brick elevated iron wire, and specimen higher than the iron pan were added. After placing the specimen on the iron wire, the top of the sealing box was covered with a preservative film. The sealing box was then closed, and sealed with a piece of parafilm. The whole package was set aside for more than two weeks as the environment simulating indoor humidity changes. The λ was measured by the Heat Flow Meters to know the influence of the MC difference in the specimens on λ in different RH environments.

Determination of temperature variation and λ

The specimen was then taken out of conditioning room to measure the weight for its basic properties. The specimens were then placed in the oven at 50, 70, and 90°C for 12 h. Afterwards, the λ was determined to know the effect of wood temperature variation by using a portable Heat Flow Meters.

Statistical analysis

The λ of the specimens was analyzed by Statistical Product and Service Solutions (SPSS) 12.0, and compared by Duncan's multiple range test, in which ρ<0.05 represents a significant difference. The linear dependence between variables was evaluated by statistical analysis of the correlation difference (r^2). The correlation difference was displayed by a scatter diagram. Additionally, the increase rate (IR) was calculated using the coefficient of variation (CV), and linearly estimated by linear regression equation of correlation.

RESULTS AND DISCUSSION

Influence of Taiwan's coniferous and broadleaf species on λ

The specimens were represented by abbreviated scientific names with density (specimen codes). The 11 specimens, coniferous and broadleaf species, were conditioned at a constant temperature 25°C and 65% RH in the conditioning room for three weeks. The *Cunninghamia lanceolata* (Cl–0.42) had a higher average MC of 13.86%, with a standard deviation of 0.57 (Table 1). According to the densities of coniferous and broadleaf species, the density ranges of Cl–0.42 was 0.41 to 0.43 g/cm^3, and the density range of *Chamaecyparis formosensis* (CF–0.44) was 0.40 to 0.48 g/cm^3. There were no significant differences between them. The density ranges of *Cryptomeria japonica* (CJ–0.45) was 0.36 to 0.54 g/cm^3. The density ranges of *Paulownia kawakamii* (PK–0.30) and *Melia azedarach* (ML–0.43) of broadleaf species were 0.28 to 0.32 and 0.42 to 0.44 g/cm^3, respectively. The density ranges of *Macaranga tanarius* (MT–0.57), *Machilus zuihensis* (MH–0.67), and *Swietenia macropnylla* (SK–0.67) were 0.54 to 0.60, 0.60 to 0.74, and 0.64 to 0.70 g/cm^3, respectively. The density ranges of *Pasania ternaticupula* (PS–0.74), *Laurocerasus phaeosticta* (LP–0.84), and *Zelkova serrata* (ZM–0.91) were 0.71 to 0.77, 0.74, to 0.94, and 0.85 to 0.97 g/cm^3, respectively.

The low, medium, and high densities of coniferous and broadleaf species were 0.30–0.45, 0.57–0.67, and 0.74–0.91 g/cm^3 as a comparison on the λ of various species. The ranges of wood density for coniferous species and λ were 0.1118 W/mK<CL–0.42<0.1616 W/mK, 0.1233 W/mK<CF–0.44<0.1887 W/mK, and 0.1148 W/mK<CJ–0.45<0.1696 W/mK. The CV of CL–0.42 was 0.18, and the of CF–0.44 was 0.21. The λ of coniferous species CL–0.42 of 0.1367 W/mK was selected as the control group, CF–0.44 was 14.11% higher, and CJ–0.45 was 4.02% higher.

Compared to the density of broadleaf species, the λ ranges of broadleaf species were 0.0953 W/mK<PK–0.30<0.1589 W/mK, 0.1169 W/mK<ML–0.43<0.1851 W/mK, 0.1325 W/mK<MT–0.57<0.1921 W/mK, 0.1542 W/mK<MH–0.67<0.2052 W/mK, 0.1398 W/mK<SK–0.67 <0.2160 W/mK, 0.1764 W/mK<PS–0.74<0.2222 W/mK, 0.1663 W/mK<LP–0.84<0.2297 W/mK, and 0.1839 W/mK<ZM–0.91<0.2700 W/mK. The density range of ML–0.43 and MT–0.57 was from 0.42 to 0.60 g/cm^3, and that of MT–0.57 was increased by 27.69%, which was the largest. The density range of MT–0.57, MH–0.67, and SK–0.67 was from 0.54 to 0.74 g/cm^3, and that of MH–0.67 was increased by 41.38%. The density range of PS–0.74 and LP–0.84 was from 0.71 to 0.94 g/cm^3, and that of PS–0.74 was increased by 56.80%, which was the largest. The density range of ZM–0.91 was from 0.85 to 0.97 g/cm^3 with a significant difference in λ.

Influence of density on λ

The internal structure of the woods, coniferous and broadleaf species, is very diversified and complex. The density of species is one of the major factors influencing the λ of the wood species (MacLean, 1941; Steinhagen, 1977; Tenwolde *et al*., 1988; Harada *et al*., 1998). The λ of air is only 0.0244 W/mK. The wood has lots of pores. The larger the pores allow more internal air and a smaller (slower) λ. Additionally, the coniferous species

Table 1. Specimen code, air-dried moisture content and density, and thermal conductivity of various species

Species	Specimen code	Air–dried moisture content (%)	Air–dried density (g/cm^3)	Thermal Conductivity (W/mK)
Coniferous				
Cunninghamia lanceolata	CL–0.42[1)]	13.86 (0.57)[2)]	0.42 (0.01)$^{\mathrm{ABI}}$[3)]	0.1367 (0.0249)$^{\mathrm{AM}}$
Chamaecyparis formosensis	CF–0.44	11.37 (0.52)	0.44 (0.04)$^{\mathrm{AIJ}}$	0.1560 (0.0327)$^{\mathrm{BO}}$
Cryptomeria japonica	CJ–0.45	12.24 (0.36)	0.45 (0.09)$^{\mathrm{BJ}}$	0.1422 (0.0274)$^{\mathrm{CMNO}}$
Broadleaf				
Paulownia kawakamii	PK–0.30	10.12 (0.21)	0.30 (0.02)$^{\mathrm{AH}}$	0.1271 (0.0318)$^{\mathrm{AM}}$
Melia azedarach	ML–0.43	11.58 (0.17)	0.43 (0.01)$^{\mathrm{BIJ}}$	0.1510 (0.0341)$^{\mathrm{BNO}}$
Macaranga tanarius	MT–0.57	12.16 (0.17)	0.57 (0.03)$^{\mathrm{CK}}$	0.1623 (0.0298)$^{\mathrm{BCP}}$
Machilus zuihensis	MH–0.67	12.66 (0.17)	0.67 (0.07)$^{\mathrm{DL}}$	0.1797 (0.0255)$^{\mathrm{CDQ}}$
Swietenia macropnylla	SK–0.67	12.49 (0.24)	0.67 (0.03)$^{\mathrm{DL}}$	0.1780 (0.0382)$^{\mathrm{CDPQ}}$
Pasania ternaticupula	PS–0.74	13.10 (0.49)	0.74 (0.03)$^{\mathrm{EX}}$	0.1993 (0.0229)$^{\mathrm{DER}}$
Laurocerasus phaeosticta	LP–0.84	12.70 (0.15)	0.84 (0.10)$^{\mathrm{FY}}$	0.1980 (0.0317)$^{\mathrm{ER}}$
Zelkova serrata	ZM–0.91	13.18 (0.08)	0.91 (0.06)$^{\mathrm{GZ}}$	0.2270 (0.0431)$^{\mathrm{FS}}$

1) Abbreviation of scientific name (specimen code)– air–dried density

2) Mean (standard deviation)

3) By Duncan's New Multiple Range Test: A–G: Air–dried density and λ of conifer/broadleaf species were compared; H, I and J; K and L; X, Y and Z with air–dried density (0.30–0.45; 0.57–0.67; 0.74–0.91); M, N and O; P and Q; R and S with thermal conductivity of various air–dried density species (0.30–0.45; 0.57–0.67; 0.74–0.9

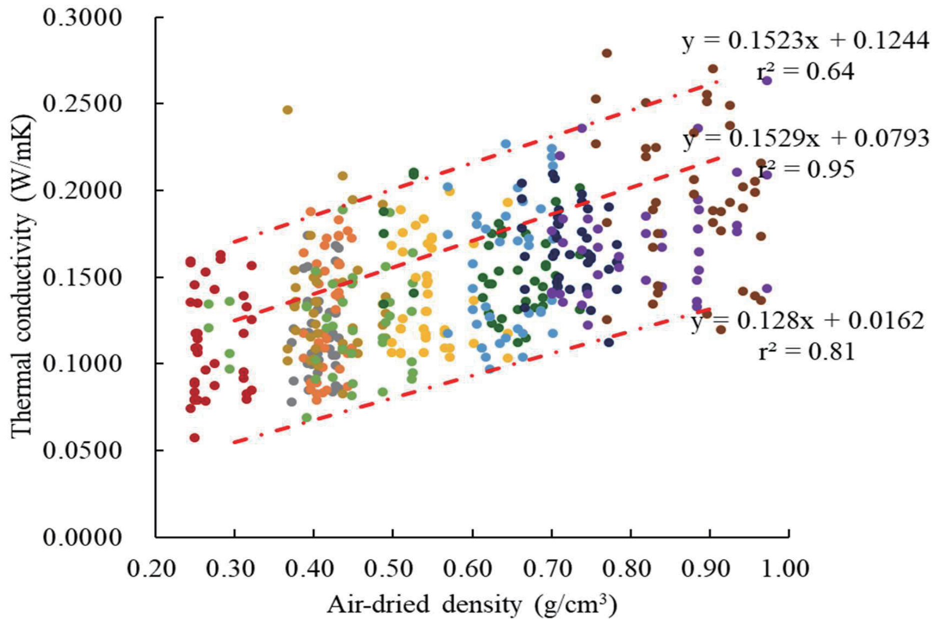

Fig. 1. Relationships between air-dried density and thermal conductivity of various species.

Legends PK-0.30; CL-0.42; ML-0.43; CF-0.44; CJ-0.45; MT-0.57; MH-0.67; SK-0.67; PS-0.74; LP-0.84; ZM-0.91

Note Abbreviation of scientific name (specimen code)- air-dried density

usually has a lower density and larger pores than broadleaf species. The λ of broadleaf species is generally higher (Siau, 1984; Peron et.al., 2020). To understand the influence of density on λ, the coniferous and broadleaf species were compared, and the result of a density range from about 0.30 to 1.00 is shown in Fig. 1.

The linear regression equation of correlation $y = 0.1523x + 0.1244$ indicated the maximum trend line of density and λ with r^2 and the slope (S) being 0.64 and 0.1523, respectively. As the λ distribution of maximum value was relatively dispersive from the linear regression line, the r^2 was lower. For the linear regression equation of correlation of $y = 0.1529x + 0.0793$, the r^2 was as high as 0.95 and S was 0.1529. This was the average trend line of λ. As it was relatively concentrated to linear regression, r^2 was higher. The S of the mean value was 0.39% higher than the maximum value, showing a smaller difference. For the linear regression equation of correlation of minimum value of $y = 0.128x + 0.0162$, r^2 was 0.81, and S was 0.1280. The S of the minimum value was 19.45% lower than the mean value. For the linear regression equation of correlation of density to λ with r^2 of 0.95, the process and range was; therefore, $y = 0.1529x + 0.0793$, with $0.30\ g/cm^3 < density < 1.00\ g/cm^3$.

Table 2 shows the correlation between the wood species and air–dried density. According to the linear regression of maximum value, mean value, and minimum value of all densities and low, medium, and high densities, the highest r^2 of the mean value of all specimens was 0.95, and the maximum IR was 66.06%.

To the comparison of different density intervals, when the low density was between 0.30 and 0.45 g/cm^3, the trend r^2 of the maximum value of λ was smaller than 0.31, the minimum value was larger than 0.64, and the IR was as high as 19.47%. It was the lowest density. When the medium density was between 0.57 and 0.67 g/cm^3, the r^2 of minimum value of mean values was smaller than 0.73, but the IR was as high as 40.74. The r^2 of the mean value was the maximum of 1.00, and IR was 25.18%. Therefore, the maximum r^2 was used in the mean value. When the high density was between 0.74 and 0.91 g/cm^3, the r^2 of the minimum value was 0.60, and IR was 6.74%. This was the minimum value in the high–density interval. The r^2 of maximum value was the largest in the high–density interval, which was as high as 0.96, and IR was 33.19%. The r^2 of the minimum value was 0.60 and IR was 6.74%, which was the minimum in the high–density interval.

When the r^2 range of the densities of various wood species was from 0.64 to 0.95, the IR difference was 12.64%. The r^2 range of low density was from 0.31 to 0.64. The IR difference was 7.59%, when the r^2 of medium density was 0.73 to 1.00. The IR difference was 20.50%, when the r^2 range of high density was from 0.60 to 0.96. The IR difference was 26.45. Yu *et al.* (2011) reported that the λ of wood increases with its density. According to the comparison of different wood species, the range of r^2 was 0.64 to 0.95, the IR difference was 12.64%, and the mean value had the maximum r^2 and IR. The λ of coniferous and broadleaf species; therefore,

Table 2. Correlations between various species and air-dried density

Air–dried Density (g/cm^3)	Specimen code 1)	λ 2) (W/mK)	y=ax+b	r^2	IR (%)
All species	PK–0.30 CL–0.42 ML–0.43 CF–0.44 CJ–0.45 MT–0.57 MH–0.67 SK–0.67 PS–0.74 LP–0.84 ZM–0.91	0.2793	y = 0.1523x + 0.1244	0.64	60.49
		0.1446	y = 0.1529x + 0.0793	0.95	66.06
		0.0283	y = 0.1280x + 0.0162	0.81	53.42
0.30–-0.45 (g/cm^3)	PK–0.30 CL–0.42 ML–0.43 CF–0.44 CJ–0.45	0.2467	y = 0.2944x + 0.0719	0.31	15.79
		0.1223	y = 0.1459x + 0.0831	0.61	11.88
		0.0283	y = 0.1321x + 0.0193	0.64	19.47
0.57–0.67 (g/cm^3)	MT–0.57 MH–0.67 SK–0.67	0.2269	y = 0.1392x + 0.1242	0.80	20.24
		0.1490	y = 0.1665x + 0.0673	1.00	25.18
		0.0968	y = 0.1531x + 0.0048	0.73	40.74
0.74–0.91 (g/cm^3)	PS–0.74 LP–0.84 ZM–0.91	0.2793	y = 0.4182x + 0.0963	0.96	33.19
		0.1772	y = 0.1509x + 0.0829	0.62	13.90
		0.1121	y = 0.0485x + 0.0778	0.60	6.74

1) Abbreviation of scientific name (specimen code)– air–dried density

2) λ, y=ax+b, r^2, and IR: the linear regression of maximum value, mean value, and minimum value of all densities and low, medium, and high densities

increased in linear correlation.

Influence of MC difference on λ of wood species in different RH environments

Different wood species have different densities and different porosities of internal structures. The specimens were placed in different RH environments. The wood species with different densities absorbed moisture differently, leading to different MC distributions (MacLean, 1941; Peron *et al.*, 2020). Figure 2 shows the influence of MC difference on λ of coniferous and broadleaf species for air–dried density in different RH environments. The MC changed was about from 4.0 to 20.0%. The relative densities had very close trends, and the interval of lower density had a steeper linearity. The specimens with lower densities had more pores and higher MC. The effect of MC was greater, and the thermal conduction was faster. The specimen with higher density had a lower porosity, and the absorbed moisture was lower, leading to lower MC and lower λ.

Table 3 shows the correlation between wood densities and λ in different RH environments. According to the comparison between coniferous and broadleaf species, the r^2 range of coniferous species was from 0.48 to 0.63. Among them, CJ–0.45 had a maximum of S 0.0095, and its IR was as high as 100.62%. Compared to CL–0.42, with a minimum IR of 36.78%, CJ–0.45 with a maximum IR was reduced by 63.84%. The r^2 range of broadleaf species was from 0.32 to 0.88, showing a significant difference. The maximum IR of SK–0.67 was 38.18%.

Based on the comparison among low-density (0.30–0.45), medium–density (0.57–0.67), and high–density (0.74–0.91), the S range of low–density interval was from 0.0063 to 0.0095. The CF–0.45 had the largest S. PK–0.30 and CL–0.42 had the smallest S. The r^2 range was 0.48 to 0.84 and the PK–0.30 had the largest r^2. CL–0.42 had the smallest value. The maximum IR of low density was 100.62, and the minimum was 34.24%. The minimum IRPK–0.30 was taken as the control group. Compared to CL–0.42 with the same S, the IR was increased by 2.54%. Compared to ML–0.43 and CF–0.44 with similar S, the S of CF–0.44 and IR increased by 7.14%, and 8.52%, respectively.

In the medium–density interval, the range of S was from 0.0042 to 0.0049. MH–0.67 had the largest S and MT–0.57 had the smallest value. The range of r^2 was from 0.32 to 0.88. The MH–0.67 had the largest r^2 and PK–0.30 had the smallest value. The maximum IR of medium density interval was 38.18%, and the minimum was 28.46%. Therefore, when PK–0.30 with minimum S was taken as the control group, in comparison to MH–0.67 with maximum S, S was increased by 16.67%, and IR was increased by 8.32%.

In the high–density interval, the range of S was from 0.0014 to 0.0039. The PS–0.74 had the largest S and ZM–0.91 had the smallest value. The range of r^2 was from 0.37 to 0.72. PS–0.74 had the largest r^2 and ZM–0.91 had the smallest value. The maximum IR of high density was 36.27%, and the minimum was 10.11%.

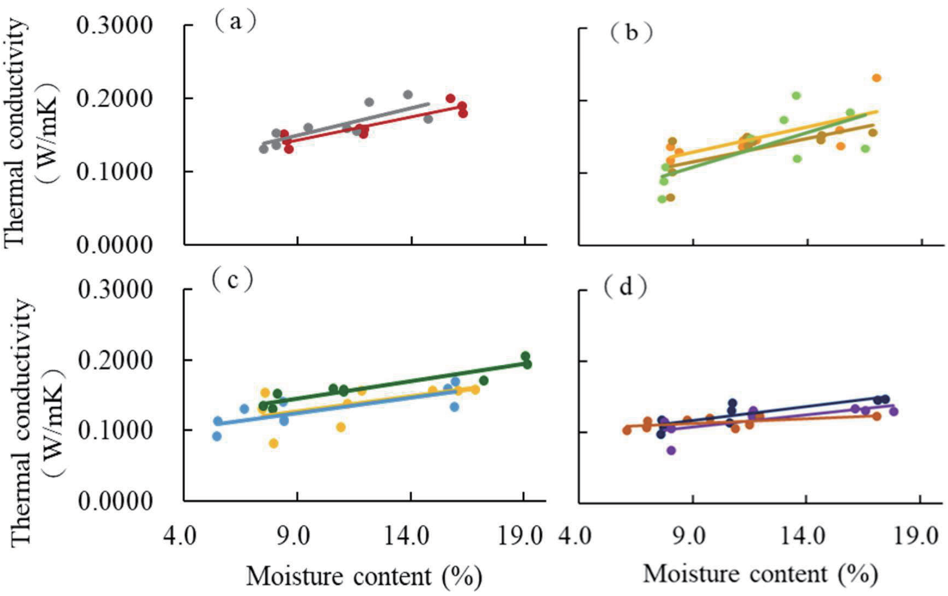

Fig. 2. Influence of moisture content on thermal conductivity of various species with different air-dried densities under different relative humidity environments.

Legends (a) PK-0.30; CL-0.42;
(b) ML-0.43; CF-0.44; CJ-0.45;
(c) MT-0.57; MH-0.67; SK-0.67;
(d) PS-0.74; LP-0.84; ZM-0.91

Note Abbreviation of scientific name (specimen code)- air-dried density

Table 3. Correlation of density of various species and thermal conductivity under different relative humidity environments

Species	Density (g/cm³)	Type of porous	Specimen code[1)]	λ (W/mK)	y=ax+b	r^2	IR (%)
Conifer species	0.30–0.45	Spring fall wood	CL–0.42	0.1367	y = 0.0063x + 0.0594	0.48	36.78
			CF–0.44	0.1560	y = 0.0075x + 0.0818	0.63	45.87
			CJ–0.45	0.1422	y = 0.0095x + 0.0229	0.51	100.62
Broadleaf species		Diffuse porous	PK–0.30	0.1271	y = 0.0063x + 0.0852	0.84	34.24
		Ring porous	ML–0.43	0.1510	y = 0.0070x + 0.0662	0.53	37.35
	0.57–0.67	Diffuse porous	MT–0.57	0.1263	y = 0.0042x + 0.0880	0.32	28.46
		Diffuse porous	MH–0.67	0.1797	y = 0.0049x + 0.1018	0.88	36.78
		Diffuse porous	SK–0.67	0.1780	y = 0.0044x + 0.0856	0.64	38.18
	0.74–0.91	Radio porous	PS–0.74	0.1993	y = 0.0039x + 0.0810	0.71	36.27
		Diffuse porous	LP–0.84	0.1980	y = 0.0034x + 0.0774	0.50	33.44
		Ring porous	ZM–0.91	0.2270	y = 0.0014x + 0.0997	0.37	10.11

[1)] Abbreviation of scientific name (specimen code)– air–dried density

Taking the minimum S of ZM–0.91 as the control group, in comparison to the PS–0.74 with maximum S, the S was increased by 178.57%, and the IR was increased by 26.16%.

Wood is a porous material and can regulate temperature, and the porosity of wood can influence its thermal property (MacLean, 1941; Kollmann and Wilfred, 1967). The wood species were compared with types of pores in Table 3. Coniferous species is non–porous wood. The spring and fall woods were apparent with the range of S being from 0.0063 to 0.0095. The IR range of spring and fall woods is from 36.78 to 100.62%.

The CJ–0.45 with the highest density had the largest IR. From low to high density, the ascending order of IR is 36.78<45.87<100.62%. Compared to the diffuse-porous wood PK–0.30 and ring–porous wood ML–0.43 with low density, the IR difference was 3.11%, and the IR of ring–porous wood was larger than that of diffuse-porous wood, 34.24%<37.35%. The diffuse–porous woods were compared with each other in terms of medium density. The range of S was from 0.0042 to 0.0049, and the range of IR was from 28.46 to 38.18%.

Compared to diffuse–porous wood with medium density, IR was 28.46<36.78<38.18%, and MT–0.57 <MH–0.67<SK–0.67. The high density includes radial porous wood, diffuse-porous wood, and ring–porous wood. The range of S was from 0.0014 to 0.0039, and IR was 10.11<33.44<36.27%. The IR of radial porous wood PS–0.747 was larger than diffuse–porous wood LP–0.84 and larger than ring–porous wood ZM–0.91. Compared to low–density spring and fall woods, the density was the highest and the IR was the largest.

In comparing ring–porous wood and diffuse–porous wood with low density, the ring–porous wood had a larger IR. For medium–density diffuse-porous wood, IR increased with density. In comparing three wood species with high density, the radial porous wood had a higher density than diffuse–porous wood and ring–porous wood. The MC; therefore, was influenced by structure. The moisture distribution was nonuniform, leading to a large r^2 range difference between MC variation and λ.

Influence of wood species on λ in different temperature environments

The temperature of wood is one of the major factors influencing λ (MacLean, 1941; Kollmann and Wilfred, 1967). The effect of wood on λ in different temperature environments is shown in Fig. 3. According to the comparison of four density intervals, 0.30–0.42, 0.43–0.45, 0.57–0.67, and 0.74–0.91, when the density was higher than 0.74, the λ difference was apparent at the temperature of 50°C. The λ increase amplitude was large, and the linear trend was steep. Wood is a porous material composed of cell cavities, cell walls, and intercellular spaces. The porosity was 0.77 when the wood density was 0.34, and the porosity was 0.49 when the density was 0.80 (Peron *et al*., 2020). The wood porosity is inversely proportional to density (Bortolin *et al*, 2013). According to the comparison between coniferous and broadleaf species, the r^2 range of softwood was from 0.89 to 1.00. The maximum value of S was 0.0011, the minimum value was 0.0003, and the CL–0.42 had the largest S. The CF–0.44 had the largest IR of 20.76%, lower than the IR of CJ–0.45 by 11.14%. The r^2 range of hardwood was 0.82 to 0.99, and the maximum IR of ZM–0.91 was 77.67%.

According to the comparison of low density (0.30–0.45 g/cm^3), medium density (0.57–0.67 g/cm^3), and high density (0.74–0.91 g/cm^3), the S range of low–density interval was from 0.0003 to 0.0011. PK–0.30 and CL–0.42 had the largest S, ML–0.43 and CJ–0.45 had the smallest S. The range of r^2 was from 0.89 to 0.99, CL–0.42 had the largest r^2, and CJ–0.45 had the smallest value. The maximum IR of low density was 39.02%, and the minimum was 9.62%. When the CJ–0.45 with mini-

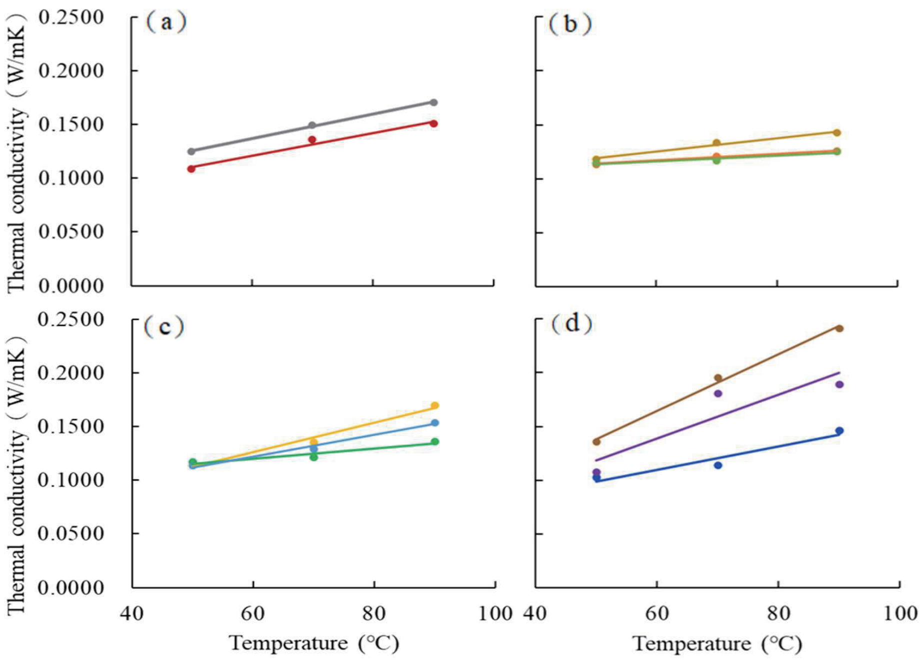

Fig. 3. Influence of thermal conductivity of each species with air-dried densities under different temperature environments.

Legends (a) PK-0.30; CL-0.42;
(b) ML-0.43; CF-0.44; CJ-0.45;
(c) MT-0.57; MH-0.67; SK-0.67;
(d) PS-0.74; LP-0.84; ZM-0.91

Note Abbreviation of scientific name (specimen code)- air-dried density mum IR was taken as the control group, the IR of MS–0.43 with the same S was 36.84%, and the IR was increased by 27.22%. The IR difference between the maximum IR of 39.02% of PK–0.30 with close S and the IR of 10.76% of CL–0.42 was 28.26%.

In the medium density interval, the range of S was 0.0005 to 0.0014. MT–0.57 had the largest S and its IR was 47.91%. MH–0.67 had a minimum IR of 16.17%. MH–0.67 with minimum IR was taken as the control group, compared to MT–0.57 with maximum IR, and the IR was increased by 31.74%. The range of r^2 was from 0.91 to 0.98, SK–0.67 had the largest r^2, and MH–0.67 had the smallest value.

In the high–density interval, ZM–0.91 had the largest S, and LP–0.84 had the smallest value. The range was 0.0011 to 0.0026, and the range of r^2 was 0.8213 to 0.9938. The maximum IR of high density was 77.67%, and the minimum was 42.58%. The PS–0.74 with minimum S was taken as the control group. Compared to the ZM–0.91 with maximum S, the S was increased by 136.36%. The IR was increased by 35.09%.

Peron *et al.* (2020) report that the coniferous species had more pores than broadleaf species, the λ of broadleaf species was higher. The coniferous species density was usually low, contained more pores, leading to a lower λ. The porous wood types of various wood species were compared in Table 4. The coniferous species is non–porous wood, and spring and fall woods were apparent with the range of S ranging from 0.0003 to 0.0011. The IR range of spring and fall woods was from 9.62 to 20.76%. The density range was 0.42–0.45 g/cm^3 and the ascending order of IR is 9.62<10.76<20.76%.

Compared to diffuse–porous wood PK–0.30 and ring–porous wood ML–0.43 with low density, the PK–0.43 had a larger S than ML–0.43, and the IR difference was 28.26%. As a result, the IR of ring–porous wood was smaller than that of diffuse–porous wood, 36.84%<39.02%. The diffuse–porous woods with medium density were compared with each other. The MT–0.57 had the largest S, and MH–0.67 had the smallest value ranging from 0.0005 to 0.0014. The range of IR was from 16.17 to 47.91%.

According to the comparison of diffuse–porous woods with medium density, IR was MH–0.67 (16.17%) < SK–0.67 (35.59%) < MT–0.57 (47.91%). According to the comparison of radial porous wood, diffuse–porous wood, and ring–porous wood with high density, the range of S was from 0.0011 to 0.0026. The ZM–0.91 had the maximum value and PS–0.74 had the minimum value. The IR of PS–0.74 was 42.58<75.46 of LP–0.84<77.67 of ZM–0.91. The IR of radial porous wood PS–0.74 was smaller than that of diffuse–porous wood LP–0.84 and smaller than that of ring–porous wood ZM–0.91. Therefore, in comparing low–density spring and fall woods, the maximum density had the minimum IR.

For low–density ring–porous wood and diffuse–porous wood, the ring-porous wood had a smaller IR than diffuse–porous wood. For medium–density diffuse–porous woods, the lower the density wood had a higher IR. For high–density wood, the radial porous wood was smaller than diffuse–porous wood and smaller than ring–porous wood. In terms of various wood species densities, the λ increased with temperature. The temperature was positively correlated with λ. Moreover, the different pore arrangement patterns of broadleaf species resulted in differences (MacLean, 1941; Kollmann and Wilfred, 1967).

According to the influence of temperature and MC on λ, the r^2 range of different temperatures was from 0.82 to 1.00. A larger r^2 to λ represented a smaller correlation between specimens. The temperature variation had a greater influence on heat conduction in the case of high–density. The r^2 range of MC difference in different RH environments was from 0.32 to 0.84, and the r^2 to λ was smaller. This means that the difference between specimens is larger, and the temperature had greater effects on λ than MC. In other words, the thermal conduction changes greatly in the tests for various wood species with different densities and temperature variation.

Table 4. Correlation of density of various species and thermal conductivity under different temperature environments

Species	Density (g/cm^3)	Type of porous	Specimen code[1]	λ (W/mK)	y=ax+b	r^2	IR (%)
Conifer species	0.30–0.45	Spring fall wood	CL–0.42	0.1367	y = 0.0011 x + 0.0678	1.00	10.76
			CF–0.44	0.1560	y = 0.0006 x + 0.0885	0.97	20.76
			CJ–0.45	0.1422	y = 0.0003 x + 0.0994	0.89	9.62
Broadleaf species		Diffuse porous	PK–0.30	0.1271	y = 0.0011 x + 0.0576	0.97	39.02
		Ring porous	ML–0.43	0.1510	y = 0.0003 x + 0.0987	0.97	36.84
	0.57–0.67	Diffuse porous	MT–0.57	0.1263	y = 0.0014 x + 0.0437	0.98	47.91
		Diffuse porous	MH–0.67	0.1797	y = 0.0005 x + 0.0915	0.91	16.17
		Diffuse porous	SK–0.67	0.1780	y = 0.0010 x + 0.0615	0.98	35.59
	0.74–0.91	Radio porous	PS–0.74	0.1993	y = 0.0011 x + 0.0444	0.93	42.58
		Diffuse porous	LP–0.84	0.1980	y = 0.0020 x + 0.0170	0.82	75.46
		Ring porous	ZM–0.91	0.2270	y = 0.0026 x + 0.0063	0.99	77.67

[1] Abbreviation of scientific name (specimen code)– air–dried density

CONCLUSION

This study used different domestic coniferous and broadleaf species to investigate the influence of different densities on λ, and also used the MC difference in various wood species in different RH environments, and the temperature variation in different environments to evaluate the influence on λ. The results were concluded as follows:

1. The λ range of various wood species with an air–dried MC of 10–12% was from 0.0283 to 0.2793 W/mK. When the MC was in a steady state, a slight influence of λ was observed.
2. The λ range of various wood species with air–dried density from 0.30 to 1.00 g/cm^3 was 0.1367–0.2270 W/mK. The higher the density was, the faster the λ was; the lower the density was, the higher the porosity was, and the slower the λ was.
3. The difference in moisture absorption of wood resulted in MC difference. After moisture absorption, the wood species with higher MC had higher λ. The λ of MC of 4–20% was from 0.1090 to 0.1900 W/mK.
4. The density of various wood species was 0.30–1.00 g/cm^3. When the temperature was used as a factor influencing λ, the temperature increased from 50 to 90°C. The λ range was from 0.1024 to 0.2411 W/mK, the r^2 was from 0.82 to 1.00, and the λ of various wood species increased with temperature variation.

AUTHOR CONTRIBUTION

Mei–Fan Kuo performed the course/experiments and evaluated data with the statistical analysis. Noboru Fujimoto supervised the work. Han Chien Lin designed the study and wrote this paper. The authors assisted in editing of the manuscript and approved the final version.

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