

2.5 Model evaluation and validation

Model analysis and simulation are commonly used tools for engineering researchers. Some definitions and guidelines for modeling research were given by the CAMASE News (1995, On-line). Evaluation is "the broadest term to describe the action of judging the adequacy of a model. Evaluation includes checking internal consistency and units used in a computer program, comparison of model output with an independent data set of real world observations, uncertainty analysis, and judgment of utility." Validation is commonly thought of as "establishing the usefulness and relevance of a model for a predefined purpose." Models usually have a limited range of validity because of the assumptions made before setting up the models. A major part of the validation consists of an assessment of prediction accuracy. Some guidelines for the evaluation and validation process when dealing with the complex models are given as (translated from German): "1).If the subject of a model is too long time for regular validation (e.g. an entire region), the model is to be subdivided into components that are validated separately. ...2).If the subject of the model is taking too long time for regular validation, validation should be undertaken for shorter periods and indirect evidence."

Experimental tests for seeking the transverse thermal conductivities of the three species modeled in this study were performed to evaluate the model outputs and validate the model predictions. The models have predicted the thermal conductivities as influenced by moisture content and latewood percentage in a large range. It is not possible to evaluate the whole model outputs, only several values were compared under certain specified conditions. To validate the model prediction accuracy, the tendency for the thermal conductivity change in the specified ranges predicted by the models was logically assessed.

2.5.1 Material and Methods

2.5.1.1 Sample preparation

Two softwood species -- southern yellow pine (*Pinus spp.*) and Scots pine (*P. sylvestra*), one hardwood species -- soft maple (*Acer rubrum*) were chosen for the model evaluation tests. Southern yellow pine and maple were bought from local lumber companies. Scots pine boards were shipped from EMPA, Switzerland. All the boards were commercial boards selling on the market. So the moisture contents for the boards ranged from 8% to 12%.

The testing equipment for thermal conductivity measurement is the R-MATIC guarded Heat Flow Meter Thermal Conductivity Instrument from Dynatech R/D Company. The testing method for this heat flow meter is based on ASTM C518 and ISO 2581. The testing sample in the R-MATIC is held between two temperature-controlled plates of which the lower one can be raised or lowered to any desired plate spacing. The plate temperatures are measured using platinum resistance temperature sensors. The cold plate of the R-MATIC can be maintained at a temperature below ambient by means of a Freon cooling system and a controlled heater element. Thus, a mean sample temperature of 75°F (or 24°C) can be easily obtained with any reasonable temperature gradient through the sample. The chamber's size for the samples is 24"x24". Heat flow through samples is measured with a specially constructed heat flow meter which completely covers a 10"x10" area in the center of the chamber.

Based on the specification of the R-MATIC instrument, at least a 10"x10" surface size for the samples is required for the thermal conductivity test. For consideration of the data reliability, all the wood samples in this test were prepared with 12"x12" contacting surfaces and crammed into the center of a Styrofoam holder, which has the same size as the testing chamber (24"x24") and a square 12"x12" hole cut out from its center. Extruded Styrofoam was used to locate the wood samples in the center of the testing chamber to ensure the heat flow through the wood sample, and prevent the heat flow disturbance from the four sides of the sample. Figure 2.47 shows the testing sample in a Styrofoam holder before placing into the R-MATIC testing instrument.

To measure thermal conductivity in the radial and tangential directions, samples have to be prepared with very good ring orientation in the thickness direction, which is also the heat flow direction. For testing radial thermal conductivity, heat flow has to be in the radial direction with the ring oriented parallel to the top and bottom surface in the thickness direction of the samples (Figure 2.48). And tangential thermal conductivity testing samples have to have the ring orientation perpendicular to the two surfaces as shown in Figure 2.49. With a 12"x12" surface, it is very hard to obtain one piece of wood with the very good ring orientation as specified above. So, two to four pieces were glued together to form one testing sample. This sample preparation gave limitations on the time and numbers of more replications. Only two replications for each test were carried out in this study as listed in *Table 2.11*. An example of the radial and tangential thermal conductivity testing samples is shown in Figure 2.50. Although a diligent effort was made to obtain very good ring orientation as specified, small deviations from the required

orientation can be found in the prepared samples as seen in the Figure 2.48 and 2.49. These deviations introduced some errors in the measurement results as analyzed later.

Table 2. 1 Number of testing specimens for each test specified.

	Southern yellow pine		Scots pine		Soft maple	
	radial k	tangential k	radial k	tangential k	radial k	tangential k
# of specimen	2	2	2	2	2	2



Figure 2. 1 Testing sample, set up and R-MATIC instrument.

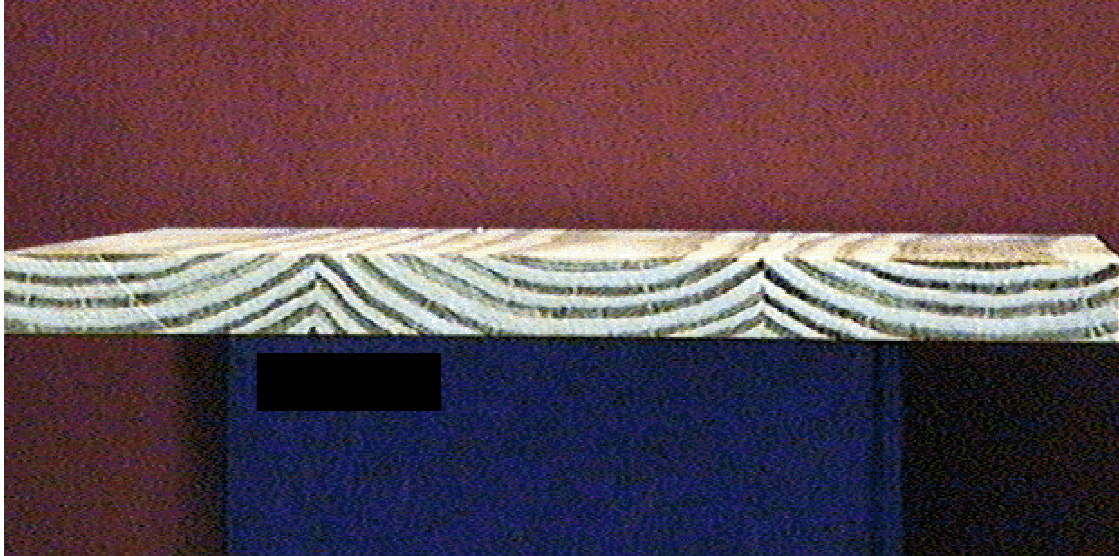


Figure 2. 2 An example show of the ring orientation at the end of a radial testing board with three pieces glued together for measuring the radial thermal conductivity.

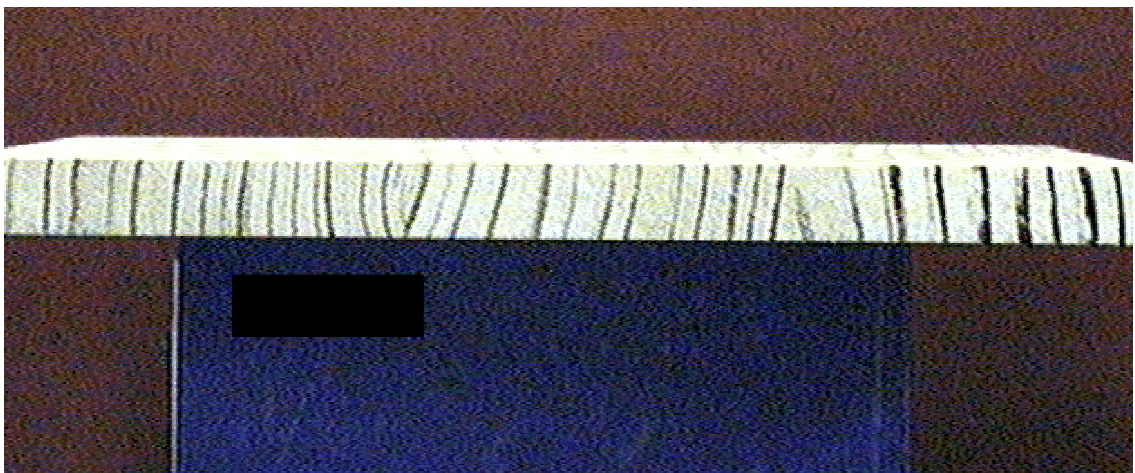


Figure 2. 3 An example show of the ring orientation at the end of a tangential testing board with three pieces glued together for measuring the tangential thermal conductivity

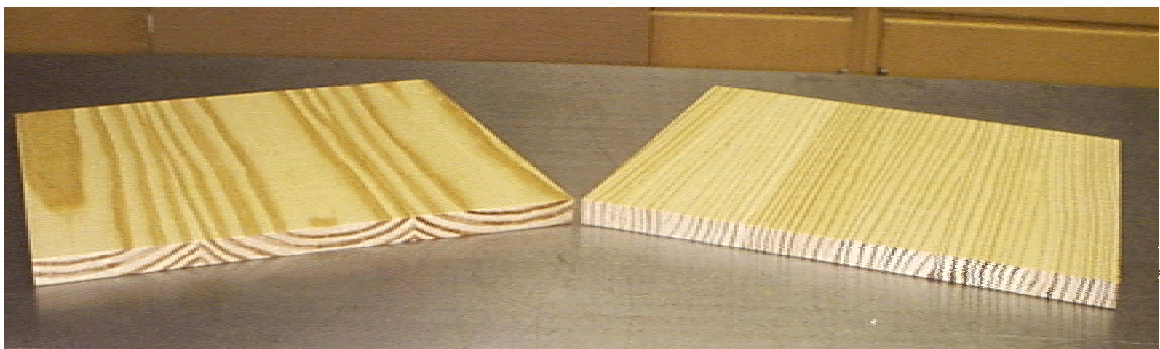


Figure 2. 4 The radial (left) and tangential thermal conductivity samples (SYP).

The wood samples were cut from the commercial boards bought from the market with MC of about 8% to 12%. Samples with certain moisture content may take a long time to obtain stabilized data after the moisture is distributed uniformly in the samples. For the consideration of time and accuracy of the testing data, only oven-dried samples were tested to compare with model outputs at 0% MC. The sample sub-pieces were oven-dried before gluing into one testing sample. It has been proved that glue lines in testing samples do not have significant effects on the thermal conductivity measured from the samples (Wangaard 1969). The glued samples were planed with a small planer to obtain smooth surfaces. The smoother the surfaces are, the better the contacts are between the sample surfaces and the heat plates in the instrument, and as a result, the lower the resistances in the heat flow are from the two contact resistances. There are three thermal resistances in heat flow for the test including the wood sample resistance. From the definition for the resistance, we know that resistance is proportional to the length of the heat flow (thickness of the sample). So the thicker the sample is, the higher the resistance is from the samples. When the testing sample's resistance is high enough to surpass the resistance from the two contact faces, the data obtained from the test are reliable to be claimed as the thermal conductivity of wood samples. Therefore it is necessary to know the minimum thickness for the testing board before the test. Preliminary tests showed that 0.5" thick samples would give the same result as the 0.88" thick and 1.34" thick samples. Previous research (MacLean 1941) also showed the sample thickness used in a similar test was 0.5" thick. Therefore 0.5"-thick board is thick enough for obtaining reliable test results.

2.5.1.2 Experimental procedure

Two samples for each test as described in *Table 2.11* were used in this study. Each sample was first planed to the thickness of 0.75" thick for testing under the four averaged temperatures -- 75°F, 80°F, 85°F, and 90°F. Then the sample was taken out from the instrument and planed to the thickness of 0.55". The thermal conductivities of the thinner samples were measured again under the same four temperature conditions.

The different thickness examined in this experiment was to investigate the possible effect of latewood percentage in the heat flow direction. By planing the sample boards into two different thicknesses, the latewood percentage in the board thickness could be changed, especially for the radial thermal conductivity testing boards. The tangential thermal conductivity testing boards might change very little for the percentage of latewood in the heat flow direction by planing the board into two thicknesses. But with less change of the LW percentage, we expected less change

on the tangential thermal conductivity values obtained from the two boards with different thickness. This was another indication to show that the LW% has an affect on the heat transport in wood. The specified thicknesses for the testing boards were chosen based on the test set ups.

The temperature effect was investigated with four test set-ups as shown in *Table 2.12*. Temperature has a positive linear affect on wood thermal conductivity, which has been studied by several earlier researchers (MacLean 1941, Kollmann 1951, Ward 1960, McNordie 1962, Steinhagen 1977). Siau (1995) concluded the results from all of the researchers and gave an explicit relation as "the thermal conductivity increases from 0.0018 to 0.0022 per °C in the hygroscopic range to 0.0035 per °C at MC=100% for temperature between 0°C and 100°C". Harade (1998) and Suileman (1999) proved this relation with a very close temperature effect coefficient as shown by *Equation 2.7* in the previous Background section 2.2.2. After experiments preformed under the four increasing average temperature conditions, explicit relations for the temperature-influenced radial and tangential thermal conductivities of the three species will be given from the regression analysis. These relations, specifically for each species and direction, were needed in the 2D heat transfer model developed in the next chapter.

Table 2. 2 The temperature set-ups on the R-MATIC instrument for each of the test.

condition	Temperature (F)		
	hot plate	cold plate	avg. Temp.
1	95	55	75
2	100	60	80
3	105	65	85
4	110	70	90

Each of the 12 tests listed in *Table 2.11* was started with 0.75" sample board, either radial board or tangential board. The 24"x24" Styrofoam holder filled with the testing board at the center was put into the R-MATIC specimen chamber, the lower plate was wheeled up until the sample was firmly clamped between the two plates. The Δx position displayed on the front panel of the instrument gave the thickness of the sample that machine sensors measured, which is close to the predefined thickness of the board after planing. The temperature for the hot plate and cold plate were set up by the controlled knobs on the front panel. Their temperatures are showing in the display window on the front panel of the instrument. The heat flow (mV) can also be read from the display window.

A period of time is required for the test chamber to reach equilibrium. This period of time varies depending on the type of materials and thickness of the materials, but usually will be between 1 to 3 hours for most materials. Data have to be recorded early before equilibrium to determine when it has been reached. Determination of reaching equilibrium is based on the ASTM specification C518: "check thermal equilibrium by observing the mean temperature and the *emf* output of the heat flow meter, the temperature drop across the specimen. Make the observations at intervals equal to the value ρCDR (ρ --density, C --thermal heat capacity, D --thickness of the specimen, R --estimated resistance for the specimen) or 300 seconds whichever is greater until five successive observations yield a thermal resistance value agreeing within 1%." The product ρCDR was calculated for all the testing samples before starting the test. The interval calculated for 0.55" thick southern yellow pine (SYP) board was about 15 minutes, and about 32 minutes for 0.75" thick SYP board. The wood species have very little effect on the interval calculated, so for convenience, the same two intervals as for SYP were used for all the species' observations with the respective board thickness.

Every sample board (total of 12) for the three species was tested with two thicknesses under each of the four temperature conditions. The hot plate temperature (°F), cold plate temperature(°F), heat flow meter output (mV), and sample thickness (in) were recorded every 15 minutes for the 0.55"-thick boards and every 30 minutes for the 0.75"-thick boards. For every single thermal conductivity measurement (total of 4x12=48 tests), 3 hours was given for reaching the equilibrium before starting to record all of the above data. And another two or three hours were taken for collecting data. If some un-stabilized data were found within this period of time, more data would be collected until the equilibrium was found. The averaged data for all the above parameters were used to calculate the thermal conductivity.

The thermal conductivity, k , was determined by the following equation:

$$k = N * Q * \frac{\Delta x}{\Delta T};$$

Equa. (2. 1)

Where, N ---- calibration constant for heat flow meter;

Q ---- heat flow meter output (mV);

Δx ---- sample thickness, (in);

ΔT ---- difference of hot plate temperature and cold plate temperature, ($^{\circ}\text{F}$);

The constant N was calibrated before starting all the tests because the R-MATIC instrument hasn't been used for a long time before this study. It needs to be re-calibrated. The calibration process and calculation for N was based on guidance from the R-MATIC instrument manual. The value for N was calculated as 4.977. The thermal conductivity calculated from Equation 2.36 has the unit of $\text{Btu}\cdot\text{in}/\text{hr}\cdot\text{ft}^2\cdot^{\circ}\text{F}$. To transfer this SI unit to the Metric unit, $\text{W}/\text{m}\cdot\text{K}$, a factor of 0.144 was multiplied.

2.5.2 Results and discussions

Due to the time limit and complicated sample preparation procedure, not too many thermal conductivity values for each direction of each species were measured in this study. So an efficient statistic experimental design model has to be used to analyze all the effects together. Factorial experimental design is a treatment design, separated from other error-reduction experimental designs (Hinkelmann & Kempthorne 1993). It is for examining the treatments, which have a factorial structure. The value for the factorial design is that it allows us to estimate the various effects and interactions simultaneously and efficiently. 2^n factorial design is usually for examining treatments at two levels to obtain some qualitative information about the possible effect of certain treatments. If quantitative information for any particular treatment effect needs to be known, then another statistical design has to be applied. 2^3 factorial experimental design model was applied to the results for the three species as shown in Table 2.13, Table 2.14 and Table 2.15. The three factors in the 2^3 factorial design model are direction (radial vs. tangential), temperature (low vs. high), and board thickness (mid vs. thin). The influences of these three factors on the thermal conductivity measured were examined by the model analysis. The purpose for this analysis is to find the significance of the factors first with a little amount of testing result and then examine further for the factors that have significant influences on the thermal conductivity values obtained.

Table 2. 3 Southern yellow pine thermal conductivity values from the experiments under the specified conditions (treatments) with one replication for each category.

	75F		85F	
	mid-thick	thin-thick	mid-thick	thin-thick
Radial	0.114	0.129	0.116	0.132
	0.111	0.111	0.116	0.113
Tangential	0.111	0.108	0.114	0.112
	0.115	0.114	0.118	0.117

Table 2. 4 Scots pine thermal conductivity values from the experiments under the specified conditions (treatments) with one replication for each category.

	75F		85F	
	mid-thick	thin-thick	mid-thick	thin-thick
Radial	0.122	0.119	0.126	0.123
	0.118	0.12	0.122	0.1235
Tangential	0.126	0.125	0.1295	0.13
	0.121	0.121	0.124	0.126

Table 2. 5 Maple thermal conductivity values from the experiments under the specified conditions (treatments) with one replication for each category.

	75F		80F	
	mid-thick	thin-thick	mid-thick	thin-thick
Radial	0.132	0.13	0.134	0.133
	0.114	0.116	0.116	0.118
Tangential	0.115	0.114	0.117	0.116
	0.099	0.103	0.1	0.104

The statistical result for SYP (table A-41 in Appendix A) showed that there is no effect from any of the three factors -- direction, temperature or board thickness. While for both Scots pine and maple, significant effects on the thermal conductivity values were found from the direction and temperature factor, but not from the board thickness (tables A-42, A-43 in Appendix A). The direction and temperature effects on the wood thermal conductivities were expected from the literature. That SYP didn't show the significance from this two effects may be due to inference from the especially high values of one of the two radial thin boards (see in *Table 2.13*). The reason for the significant increase from radial 0.75"-thick board to 0.55"-thick board on both temperature results was found to be due to the delay of tests by examining the raw data. There were several days of delay for the tests on 0.55"-thick radial board which should be done right after the 0.75" thick board tests. During these days, the thin SYP radial board absorbed

moisture from the environment and resulted in the greater values for the thin SYP radial board than it was expected if the board was oven-dried. So more tests on the southern yellow pine radial thermal conductivity measurement may need to be done in the future to re-run this analysis and re-examine the effects. The thickness effect was not found significant from all of the three factorial design analysis for the tests. This is also consistent with the result from the preliminary test on finding the optimal thickness for the testing board in R-MATIC testing instrument. So it can be concluded that 0.55" thick board is good enough to obtain the reliable data of thermal conductivity values measured from the R-MATIC instrument.

2.5.2.1 Relations between latewood percent and wood transverse thermal conductivities

Latewood percentage is an important parameter for the thermal conductivity geometric models developed above. Therefore the relations between latewood amount in the samples and thermal conductivity values for the samples obtained from the tests need to be examined. For each board tested, latewood percentage was measured using image analysis software on the images taken from the end of each board. Although the thickness of the board has been shown to have no significant effect on the thermal conductivity values from the 2³ Factorial model design, which mixed the radial and tangential testing results together, the affect of latewood percentage in the thickness direction on the results (thermal conductivity values) has not been examined specifically. A correlation test between the measured latewood % and thermal conductivity measured for each board was performed. Table 2.16, Table 2.17 and Table 2.18 show the correlation test results for SYP and Scots pine. Since there is no significant amount of latewood or latewood change for maple species, correlation tests could not be performed on maple results.

Table 2. 6 Correlation between SYP radial thermal conductivity values and latewood percentage (LW%) measured from SYP radial boards.

SYP radial board			Correlation		Correlation	
LW %	k_r 85F	k_r 75F	LW %	k_r (from 75F)	LW %	k_r (from 85F)
34.28%	0.116	0.114	LW %	1	LW %	1
45.06%	0.127	0.124	kr	0.94561538	kr	0.90073191
22.77%	0.116	0.111				
20.64%	0.113	0.111				

Table 2. 7 Correlation between SYP tangential thermal conductivity values and latewood percentage (LW%) measured from SYP tangential boards.

SYP tangential board			Correlation		Correlation	
LW %	k_t 85F	k_t 75F	LW %	k_t (from 75F)	LW %	k_t (from 85F)
34.62%	0.114	0.111	LW%	1	LW %	1
30.90%	0.112	0.108	kt	0.3788136	kt	0.31274414
33.92%	0.118	0.115				
31.49%	0.117	0.114				

Table 2. 8 Correlation between Scots pine radial thermal conductivity values and latewood percentage (LW%) measured from Scots pine radial boards.

Scots pine radial board			Correlation		Correlation	
LW %	k_r 85F	k_r 75F	LW %	k_r (from 75F)	LW %	k_r (from 85F)
34.14%	0.126	0.125	LW %	1	LW %	1
27.88%	0.123	0.119	kr	0.96411942	kr	0.96406369
27.40%	0.122	0.118				
30.75%	0.1235	0.12				

Correlation between the Scots pine tangential thermal conductivity values and latewood percentage on the tangential boards was not performed due to few data available. The latewood percentage measurement was not originally planned in the tests. It was added during the test when some indications of latewood difference between specimens were found. And the limited amount of Scots pine samples shipped from Switzerland didn't provide the chance for repeating the tests. This caused too few LW% data obtained from Scots pine testing boards.

From the correlation results, it was found that the latewood percentage has a very good correlation with the radial thermal conductivity values for both pine species, but not with the tangential thermal conductivity values for SYP. This is consistent with the model predictions above. Estimation for radial thermal conductivity from the softwood models is increasing with the LW%, and much more significant than the change of tangential thermal conductivity with the LW% (see Figure 2.29 and Figure 2.33).

It has been demonstrated by several previous studies that specific gravity is an important factor in wood thermal conductivities. If the latewood percentage in wood samples has a close

relationship with the specific gravity, it can indirectly verify the models developed above, which were set up on the basis of LW%. Several pine testing boards were measured for the specific gravity after each test. The specific gravity value and the LW% value measured from each board were examined for the correlations. The results are shown in *Table 2.19* and *Table 2.20*.

Table 2. 9 Correlation between SYP specific gravity and latewood percentage measured from testing boards

Latewood %	SG
45.06%	0.57
20.64%	0.41
30.90%	0.48
33.92%	0.44
31.49%	0.44

Correlation		
	Latewood %	SG
Latewood %	1	
SG	0.893574117	1

Table 2. 10 Correlation between Scots pine specific gravity and latewood percentage measured from testing boards.

Latewood %	SG
27.88%	0.52
27.40%	0.53
30.75%	0.53
28.88%	0.546
43.96%	0.57
48.09%	0.57

Correlation		
	Latewood %	SG
Latewood %	1	
SG	0.916433694	1

A good correlation was found between the latewood percentage and specific gravity for the two pine species. This is an expected result because the more thick-walled latewood cells in the sample, the denser the wood sample is, and the higher the specific gravity is. Latewood percentage is an indication of wood specific gravity, and thus it is an important factor in the wood thermal conductivities, too.

2.5.2.2 Relations between temperature and wood transverse thermal conductivities

A temperature effect on wood thermal conductivity has been found before (MacLean 1941, Kollmann 1951, Ward 1960, McNordie 1962, Steinhagen 1977, Siau 1995, Harade 1998 and Suileman 1999). It is examined here again to provide explicit equations for both the radial and tangential thermal conductivities of each species as functions of temperature. These relations will be used in the heat transfer model programs in the next chapter.

Statistical regression was applied to obtain the explicit relationships between thermal conductivity and temperature for each direction of each species. Figures 2.51 to 2.53 show the experimental data and predicted data for all three species. *Table 2.21* gives the equations for all the regressions.

Very good linear relationships were found for the thermal conductivities with temperature for all three species in the two directions. The slopes for radial and tangential regressions of the two softwood species are very close, but the slopes for maple radial and tangential regression are very different. This finding is also true for the intercepts (the constant term) in all the linear equations (*Table 2.21*). This may indicate that radial and tangential thermal conductivity for the two pine species are not too different from each other, but are different for the maple species.

Table 2. 11 Regression for the thermal conductivities as functions of temperature of the three species in the two directions

species	direction	regression equations
SYP	tangential	$k_t=0.00054*T+0.1016$
	radial	$k_r=0.00054*T+0.0981$
Scots pine	tangential	$k_t=0.00064*T+0.1059$
	radial	$k_r=0.00066*T+0.1034$
maple	tangential	$k_t=0.00056*T+0.0875$
	radial	$k_r=0.00081*T+0.0957$

Unit for k is W/m.K. Unit for T is Feriheight

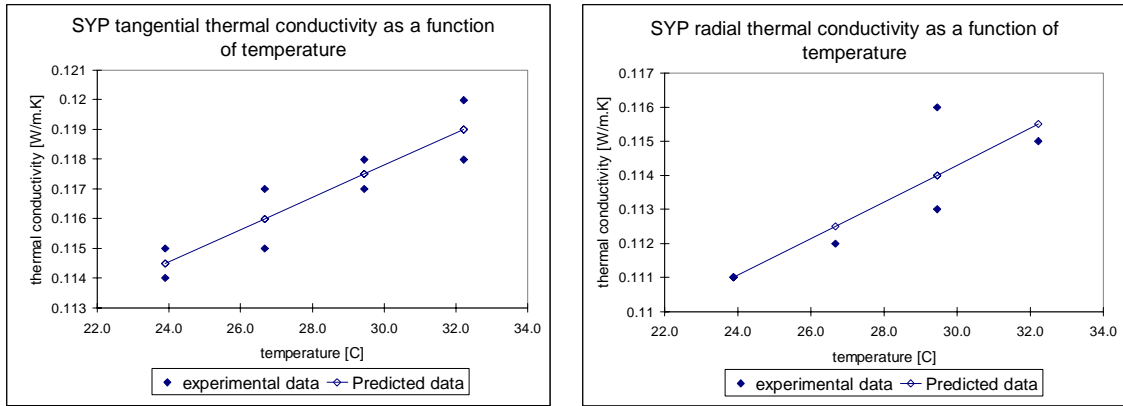


Figure 2. 5 Regression for SYP tangential (left) and radial (right) thermal conductivity as a function of temperature.

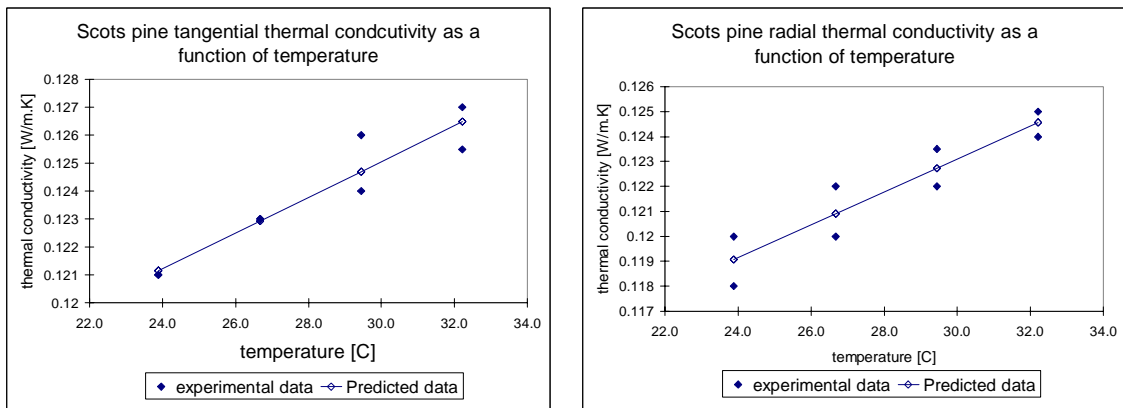


Figure 2. 6 Regression for Scots pine tangential (left) and radial (right) thermal conductivity as a function of temperature.

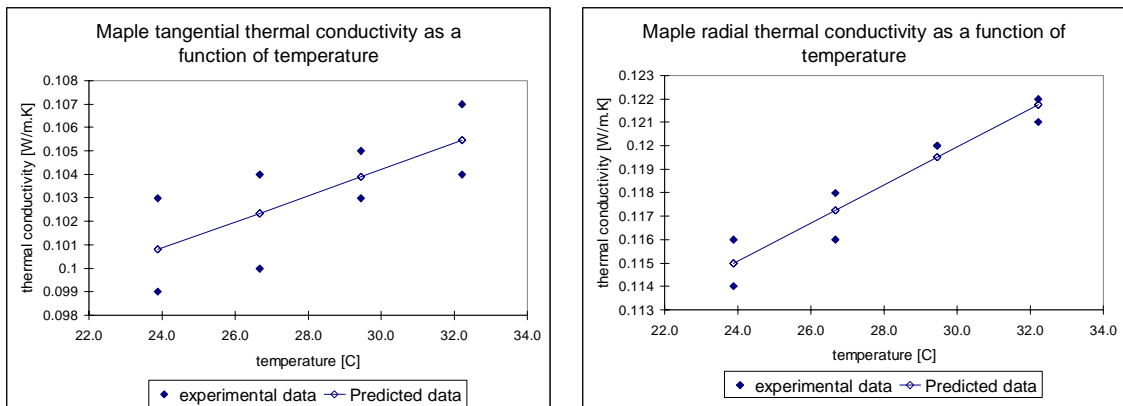


Figure 2. 7 Regression for Soft maple tangential (left) and radial (right) thermal conductivity as a function of temperature.

2.5.2.3 Comparison of radial and tangential thermal conductivity.

In the 2^3 factorial design statistical model analysis (Section 2.5.2), it was concluded that there was a *direction* (radial vs. tangential) effect on both Scots pine and maple's thermal conductivity values. The estimated thermal conductivity values by the geometric models in the previous section 2.4.1 also showed significant differences between the radial and tangential directions for all three species. But the data obtained from the experiments didn't show as much difference as the models predicted. And several tests in the literature also gave a small difference between the radial and tangential thermal conductivity. A comparison of the two directions thermal conductivity values obtained from the experiments was performed to examine the difference for all three species in order to evaluate the models' predictions.

The radial and tangential thermal conductivity of the three species were measured from different boards in the experiments, which were carefully prepared for the heat to flow in the two specified directions of wood. So the data obtained from the tests can not be compared directly for the examination due to the different boards with different specific gravities. The specific gravity (SG) was measured for each board after the thermal conductivity test. Results are shown in *Table 2.22*. The radial and tangential thermal conductivity can be compared after normalizing all the thermal conductivity values to be based on $SG=0.50$. (SG of 0.50 was chosen only as a point reference for the normalization. It can be any number from 0 to 1). The normalized thermal conductivity values are also calculated and shown in the table.

From the normalized testing result in the table, it can be easily found that there is no big difference between the radial and tangential thermal conductivity values for the two softwood species, except for a small difference sometimes. For the hardwood species, both trials give the results of higher radial thermal conductivities than the tangential ones. But the conclusions from the experiments in this study are limited and should be re-examined due to too few testing results for each category of the thermal conductivity obtained.

Table 2. 12 Thermal conductivities in two directions for the three species and specific gravities measured from the testing boards.

Trail	Species	Direction	Testing result ¹	SG	Normalized Testing result ²
#1	Southern Yellow Pine	Radial	0.129	0.57	0.113
		Tangential	0.108	0.48	0.113
	Scots Pine	Radial	0.119	0.52	0.114
		Tangential	0.125	0.546	0.114
	Soft Maple	Radial	0.13	0.58	0.112
		Tangential	0.114	0.56	0.102
#2	Southern Yellow Pine	Radial	0.111	0.41	0.135
		Tangential	0.114	0.44	0.130
	Scots Pine	Radial	0.12	0.53	0.113
		Tangential	0.121	0.57	0.106
	Soft Maple	Radial	0.116	0.53	0.109
		Tangential	0.103	0.53	0.097

¹ Testing results are based on 0.55"thick board, 75F avg. Temp

² Normalized testing result based on SG=0.5

2.5.3 Model discrepancy and uncertainty analysis

According to the estimation from the models developed in this study, significant differences can be discovered between the radial and tangential thermal conductivities. While from the test results, such significant difference was not discovered, especially for the two pine species. Higher radial thermal conductivity was infrequently found for the two pines. Maple showed the higher radial thermal conductivities than the tangential ones consistently. The raw testing results (not the normalized ones) were used to compare with the model estimations to evaluate the models developed in this study.

In order to find the estimated values of thermal conductivity for the specified testing boards from the model output table (tables A-34 to A-40 in Appendix A), the latewood percentage in the thickness direction is the index for finding the values in the tables. The latewood percentage for each testing board was measured after the thermal conductivity test. All the testing boards were oven-dried before the thermal conductivity tests, so the moisture content can be assumed to be 0%. The model-predicted thermal conductivity values for the 0% MC were compared with the testing results. Based on the LW% measured from each testing board, the corresponding thermal conductivity value from the model output table can be found and listed in

Table 2.23. The empirical results in the table were calculated from the empirical equation developed by MacLean (1941), which is a function of specific gravity of each testing board.

Table 2. 13 Testing results and models' estimations comparison for the thermal conductivity of three species.

Trail	Species	direction	Testing result ¹	Model result	Model and test discrepancy	Empirical Result ²
#1	Southern Yellow Pine	Radial	0.129	0.139	7.8%	0.138
		Tangential	0.108	0.079	-26.9%	0.12
	Scots Pine	Radial	0.119	0.121	1.7%	0.128
		Tangential	0.125	0.082	-34.4%	0.133
	Soft Maple	Radial	0.13	0.13	0.0%	0.14
		Tangential	0.114	0.092	-19.3%	0.136
#2	Southern Yellow Pine	Radial	0.111	0.125	12.6%	0.106
		Tangential	0.114	0.08	-29.8%	0.112
	Scots Pine	Radial	0.12	0.124	3.3%	0.13
		Tangential	0.121	0.095	-21.5%	0.138
	Soft Maple	Radial	0.116	0.13	12.1%	0.13
		Tangential	0.103	0.092	-10.7%	0.13

¹ Testing results are based on 0.55"thick board, 75F avg. Temp

² Empirical Equation: $k=(1.39 \times SG + 0.165) \times 0.144$ (W/m.K)

From the table and figures (Figure 2.54 and Figure 2.55) shown, it was found that radial thermal conductivity estimated by the models are close to the testing results and the empirical results for all three species, with a slightly higher than or equal to the testing results. A big discrepancy between the testing results and model estimations was found for the tangential thermal conductivities, which indicates that there may be some important structures missing in the tangential models developed.

After examining the testing samples and the theoretical model for the tangential thermal conductivity, it was found that the tangential model was developed for a too ideal situation, which is the perfect tangential situation. But in the practical world, there could never be found such perfect tangential boards. The tangential geometric model was set up on the microscopic scale observations. On the microscopic scale, tangential structure for wood is an alternating arrangement of cell wall substance and lumens. No full wall substance as a high conductive path (compare to the low conductive path with series arrangement of cell wall substance and lumens) for heat transportation in the tangential direction was assumed in the model, while this path was found in the radial direction even under the microscopic scale and included in the radial thermal conductivity model. This caused the radial model to predict good results, but the tangential model

predicted values deviated from the testing result. The tangential geometric model developed by this study is too simple and idealized. In any practical sampling boards observed under the macroscopic scale, the cell wall and cell lumen arrangement can be much complicated than the simple alternating arrangement. The full wall forming the high conductive path in the tangential direction can be found in the real wood samples. Therefore the tangential model should be modified by adding a certain percentage of side wall factor to obtain a new structure arrangement like in the radial direction: part of side wall is parallel arranged with the series combination of cell wall substance and air in both earlywood and latewood area. But it will be very hard to obtain the percentage for this part of side walls in the structure. So a simple way is taken here. An estimated factor will be applied to the model estimated tangential thermal conductivity values in order to make up the loss by the geometrical model. A factor of 1.3 was estimated for the model predicted thermal conductivities in the tangential direction based on the discrepancy calculated in the *Table 2.23*. The modified values are displayed in the amended *Table 2.24* shown below.

Table 2. 14 Amended table for thermal conductivities from testing results and modified model estimations.

Trail	Species	Direction	Testing result ¹	Model result	Model and test discrepancy	Empirical Result ²
#1	Southern Yellow Pine	Radial	0.129	0.139	7.8%	0.138
		Tangential	0.108	0.1027	-4.9%	0.12
	Scots Pine	Radial	0.119	0.121	1.7%	0.128
		Tangential	0.125	0.1066	-14.7%	0.133
	Soft Maple	Radial	0.13	0.13	0.0%	0.14
		Tangential	0.114	0.1196	4.9%	0.136
#2	Southern Yellow Pine	Radial	0.111	0.125	12.6%	0.106
		Tangential	0.114	0.104	-8.8%	0.112
	Scots Pine	Radial	0.12	0.124	3.3%	0.13
		Tangential	0.121	0.1235	2.1%	0.138
	Soft Maple	Radial	0.116	0.13	12.1%	0.13
		Tangential	0.103	0.1196	16.1%	0.13

¹ Testing results are based on 0.55" thick board, 75F avg. Temp

² Empirical Equation: $k=(1.39 \times SG + 0.165) \times 0.144$ (W/m.K)

The modified thermal conductivities in tangential direction are improving for all the three species. But the difference is always there since a couple of uncertain parameters were used in the model. For example, the thermal conductivity value for the cell wall substance was taken from the Kollmann & Malmquist (1956) result, which hasn't been re-examined since then. The thermal conductivity for the dead air in the cell lumen was taken from Maku's (1954) derivation, which gave him good agreement with the data in the literature if k_a was assigned to the value of 0.046W/m.K. This k_a value also gave good estimations for the models developed in this study.

Thermal conductivity values comparison -- testing results, theoretical model estimations and empirical model estimations-- for the three species (Trail 1)

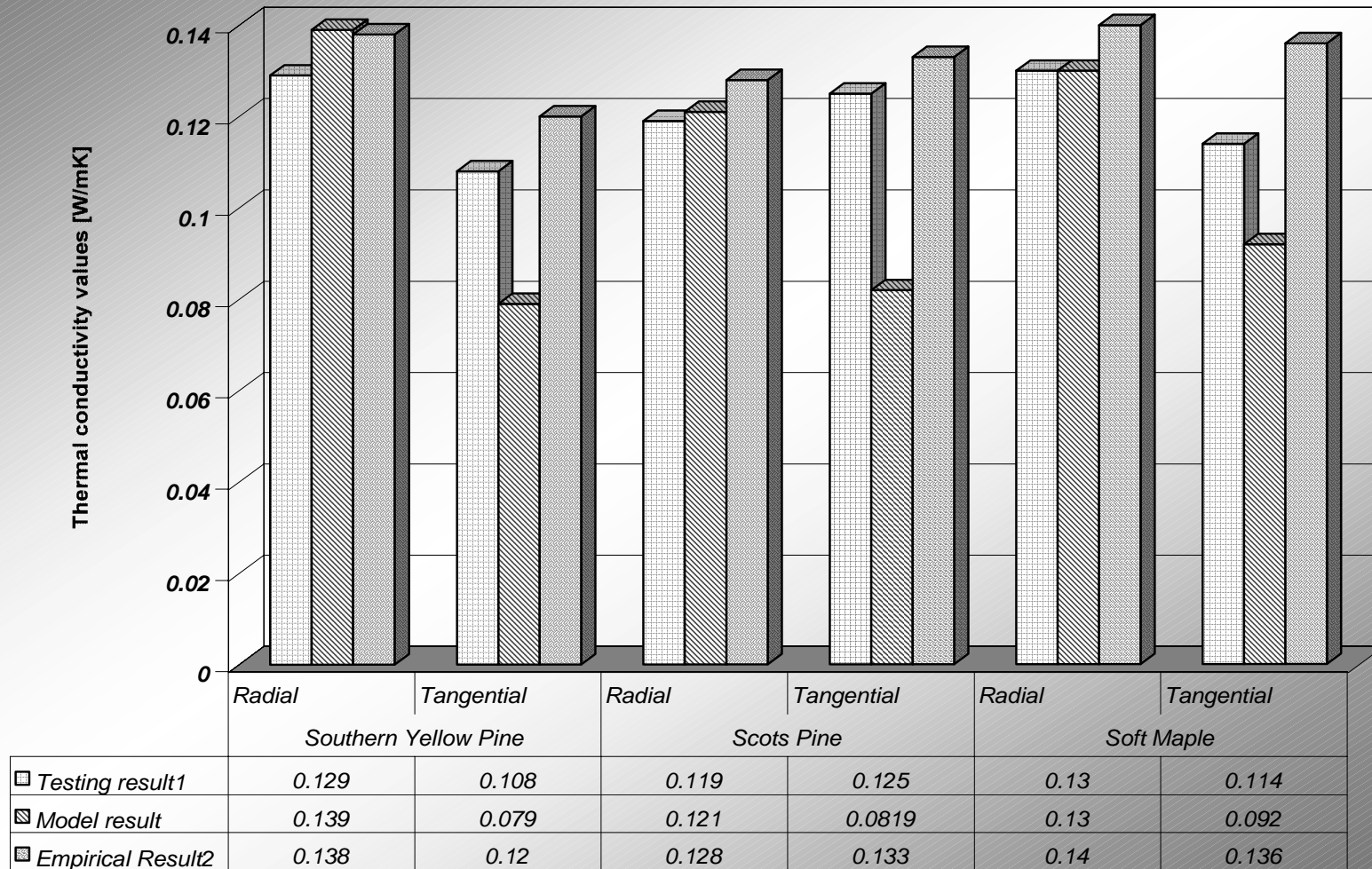


Figure 2. 8 Thermal conductivity comparison for the testing results (from trail #1) and model estimations.

Thermal conductivity values comparison -- testing results, theoretical model estimations and empirical model estimations -- for the three species (Trial 2)

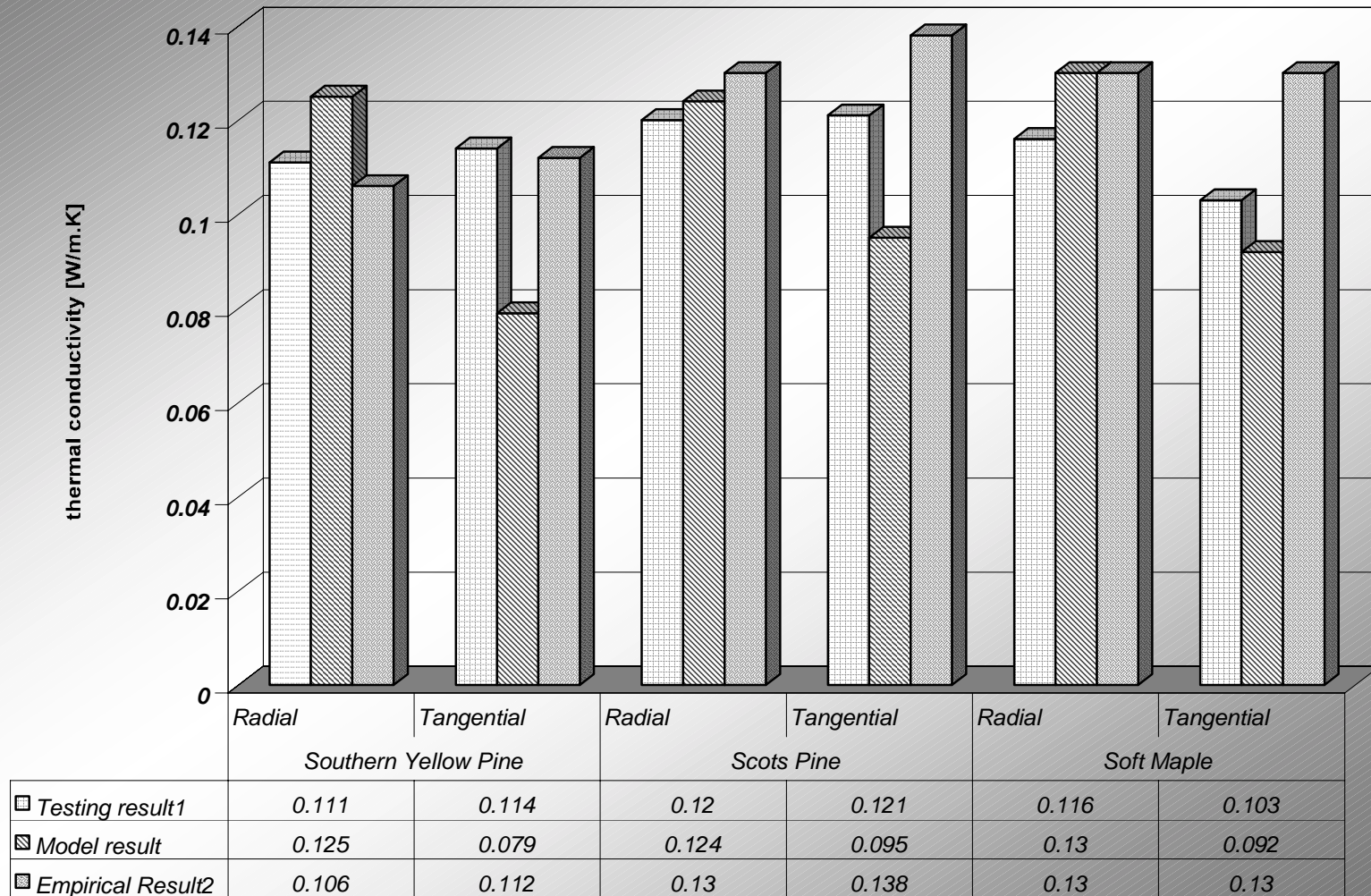


Figure 2. 9 Thermal conductivity comparison for the testing results (from trail #2) and model estimations.

Latewood percentage measured for each testing board to determine the model predicted thermal conductivity value is also an uncertain parameter. Although the advanced technique -- image analysis software -- was used for measuring the latewood percent on each sample board, some variations in the measurements with image analysis can not be prevented. Thermal conductivity predicted by the models is a linear function of LW%. 5% to 10% change of LW% will give a significant difference in the model predicting result. A Sensitivity study on the uncertain parameters is given in the following section.

2.5.4 Sensitivity study for the thermal conductivity models.

According to CAMASE News (1995, Online), "sensitivity analysis is the study of model properties through - not necessarily realistically sized - changes in the input variables and the analysis of its effect on model outputs". The sensitivity analysis in this study is to gain the insight of the relative importance for a couple of parameters utilized in the model developing process. The two parameters that were introduced from the literature to develop the model are thermal conductivity values for the two substances in wood -- cell wall substance and air in the cell lumen. The contribution from these two parameters to the model resultant wood effective thermal conductivity values was examined and compared. The sensitivity of the models was examined under the oven-dry condition (with MC of 0%) by decreasing each parameter by 10% while leaving the rest of the inputs unchanged and observing the model output's response within the whole LW% range (from 1% to 99%). The sensitivity coefficients were introduced according to Zombori's (2001) study. The sensitivity coefficient indicates the sensitivity of the dependent variable to the small change in the model input parameter. It is defined as:

$$c_x = \phi \frac{\partial X}{\partial \phi};$$

Equa. (2. 2)

Where, c --- sensitivity coefficient;

X ---- model output parameter;

ϕ ---- model input parameter;

So the sensitivity coefficients of radial and tangential thermal conductivity with respect to the change of air thermal conductivity (k_a) are defined as:

$$c_{k_R} = k_a \frac{\partial k_R}{\partial k_a};$$

Equa. (2. 3)

$$c_{k_T} = k_a \frac{\partial k_T}{\partial k_a};$$

Equa. (2. 4)

And the sensitivity coefficients with respect to the change of cell wall thermal conductivity (k_c) are calculated as:

$$c_{k_R} = k_c \frac{\partial k_R}{\partial k_c};$$

Equa. (2. 5)

$$c_{k_T} = k_c \frac{\partial k_T}{\partial k_c};$$

Equa. (2. 6)

Monitoring the sensitivity coefficients of the radial and tangential thermal conductivity with respect to the k_a or k_c change in the whole LW% range (from 1% to 99%) can provide the information on the relative importance of the two parameters and the effects of the two parameters on the model estimated thermal conductivity values. The sensitivity coefficients for southern yellow pine tangential thermal conductivity with respect to the k_a and k_c are plotted in Figure 2.56 and the sensitivity coefficients for SYP radial thermal conductivity with respect to k_a and k_c are plotted in Figure 2.57.

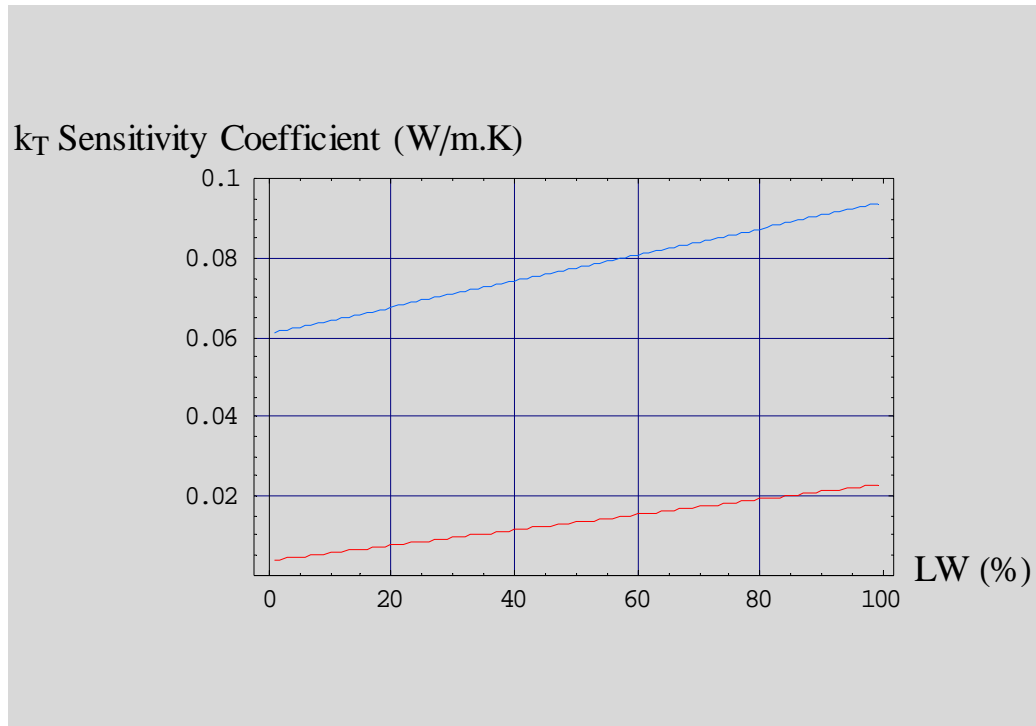


Figure 2. 10 SYP sensitivity coefficient of tangential thermal conductivity with respect to k_a (blue) and k_c (red) in the range of LW% from 1% to 99%.

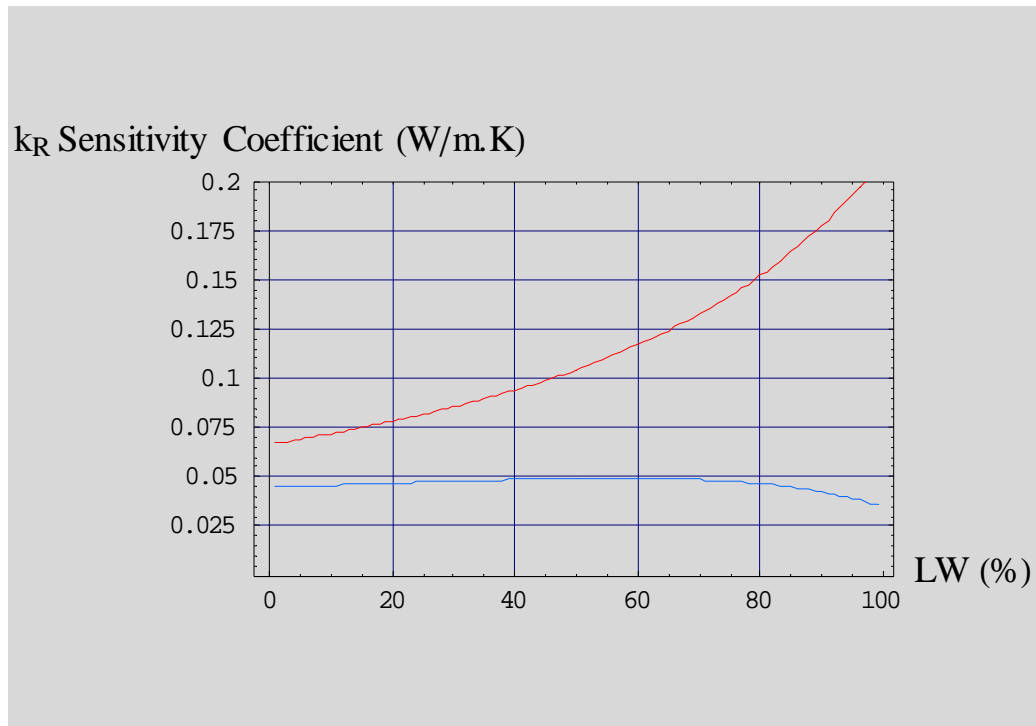


Figure 2. 11 SYP sensitivity coefficient of radial thermal conductivity with respect to k_a (blue) and k_c (red) in the range of LW% from 1% to 99%.

Since softwood species have the same geometric model and similar structure and cell wall percentage, the effects from the parameters on the model outputs should be the same. So only SYP's sensitivity coefficients were examined here as a representative for the softwoods. From the figures, it is apparent that k_a 's change has a more significant effect on the model estimated tangential thermal conductivities than k_c 's change. This is because in the softwood tangential geometric or thermal resistance model, the resistance from cell wall substance and resistance from air in the lumen are in series arrangement. While the resistance is the inverse of the conductance, then the arrangement for conductance in the wall substance and in the lumens is analogous to the electrical parallel system. So k_a and k_c are in parallel arrangement for both earlywood and latewood. k_a has a very low thermal conductivity compare to k_c . As in parallel electric circuit system, the path with low conductivity controls the total effective conductivity. So the softwood model predicted tangential thermal conductivity is sensitive to k_a 's change, and k_a 's value has an effect on the model estimations for the effective tangential thermal conductivity.

On the contrary, the radial model predicted thermal conductivity is more sensitive to k_c than k_a 's value, especially in the high LW% samples, according to Figure 2.60. In the radial geometric model for softwoods, thermal resistance from wall substance and lumen are arranged in parallel system, which indicated the series arrangement for the conductance in wall substances and lumens due the inverse function between the resistance and conductance. So k_c and k_a are in series arrangement in both earlywood and latewood area. k_c is much higher than k_a . The higher conductivity in the series system dominates the total effective conductivity. So the little change in k_c value has a more significant effect on the radial model output than k_a 's change. When LW% becomes higher and higher (above 60%), the radial model output becomes more and more sensitive to the k_c 's change due to the increased percentage of cell wall substance in the latewood area.

Sensitivity studies for hardwood thermal conductivity models were performed in the same way as for the softwood models, except that sensitivity coefficients were calculated and plotted as a function of moisture content instead of LW%. This is because the LW% in maple is assumed as a constant based on the observation of its structure. Monitoring the radial and tangential sensitivity coefficients as a function of MC provided information about how a small change of model input parameters, such as k_a or k_c , affected the model output dependent variables in the specified MC range. Figure 2.58 and 2.59 gave the sensitivity coefficients of radial and tangential thermal conductivity with respect to k_a and k_c change.

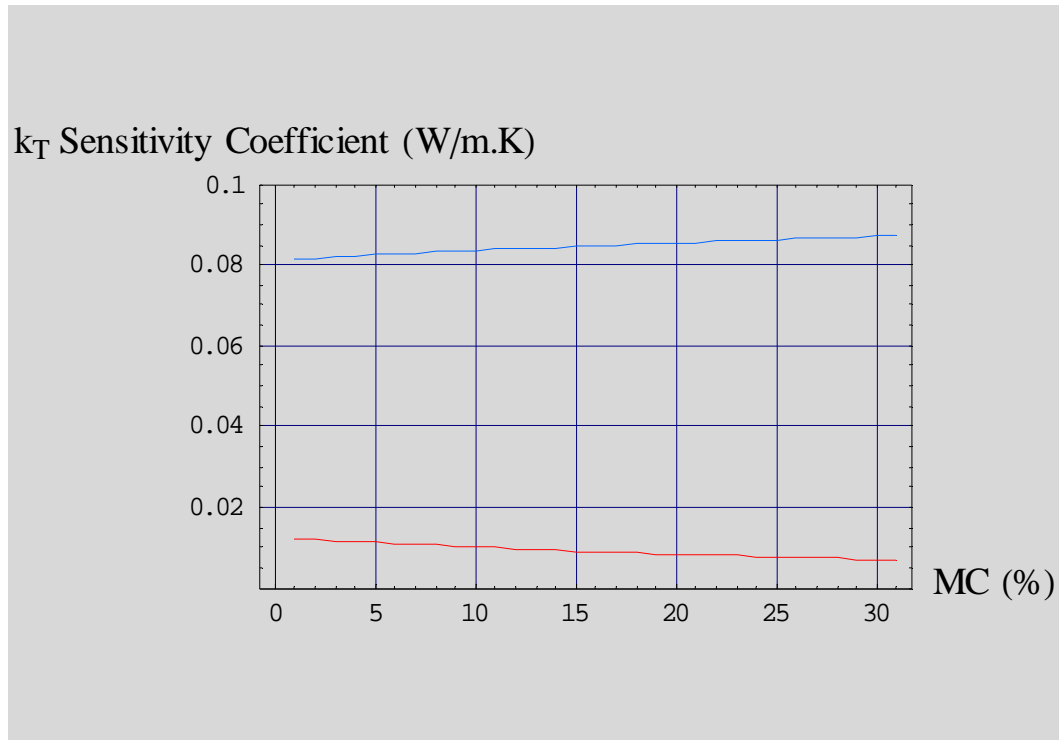


Figure 2. 12 Maple sensitivity coefficient of tangential thermal conductivity with respect to k_a (blue) and k_c (red) in the range of MC from 0% to 30%.

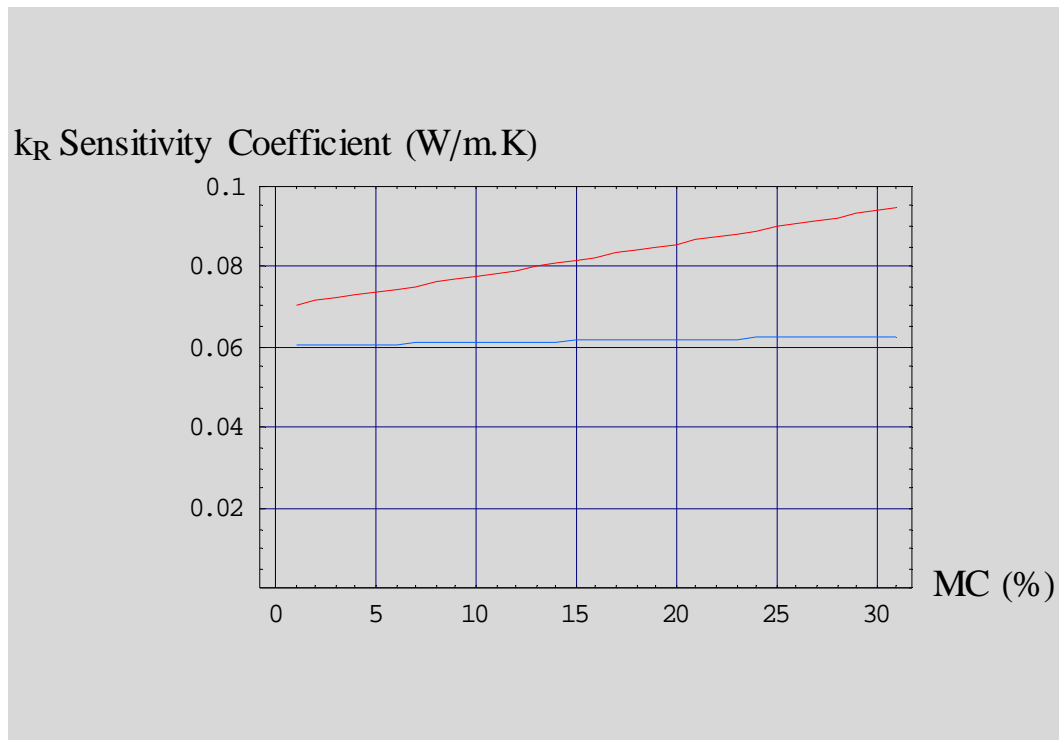


Figure 2. 13 Maple sensitivity coefficient of radial thermal conductivity with respect to k_a (blue) and k_c (red) in the range of MC from 0% to 30%.

It is apparent from the figures that the model estimated tangential thermal conductivity is more sensitive to the k_a 's change, while the radial thermal conductivity is a little more sensitive to the k_c 's change. This is the same with the softwoods models: k_a 's value has a more significant effect on the model's estimated tangential thermal conductivity values, and model's estimated radial thermal conductivity values are more affected by the k_c 's value.

2.6 Conclusion

Observation of wood anatomical structure is essential for setting up transverse thermal conductivity models as developed in this study. Observation by SEM and ESEM for the three species -- two softwood species and one hardwood species, gave the basis and requisite parameters to develop the geometric and thermal resistance models in the radial and tangential direction for both hardwood and softwood species. Results from the observation and image analysis measurements showed the structure differences between the radial and tangential direction on wood cross section, and the structure differences among the species. Softwood species have a relatively homogenous structure comparing to hardwood species. Regular (close to square) shaped cells aligned in the radial direction gave a different arrangement for the cell wall and cell lumen in the radial and tangential direction as described in the models. There is more cell wall substance in the tangential direction than in the radial direction for both softwood and hardwood species. The hardwood structure is more heterogeneous with different sized and shaped cells. Wood rays are more significant in hardwood species than in softwoods. And ray cells have a different orientation from other cells in the hardwood species, which made the modeling different from and a little more complicated than the softwoods models. The different percentage of cell wall substance in the radial and tangential direction between the dry and wet condition was examined on Scots pine samples. Statistical analysis showed that cell wall percentage in the latewood area does not change significantly from dry condition to wet condition, but in the earlywood area, cell wall percentage in the radial and tangential direction both change significantly from dry to wet condition. This was explained by the different lumen space and different wall thickness between the earlywood cells and latewood cells.

The geometric models for theoretically deriving thermal conductivities in the radial and tangential direction for softwood species and hardwood species were developed based on the anatomical structure measurements. The models were based on the wood structure observed on the cross section instead of a single cell structure, which was the basis for all the previous models. The current models included the earlywood-latewood interaction and cell wall percentage and arrangement in the two transverse directions. The analogous electrical resistance circuit was applied to generate the thermal resistance models during the derivation. The model-estimated thermal conductivities were calculated by a program written in *Mathematica* software and plotted as a function of latewood percentage in the heat transfer direction and moisture content in the samples. Model outputs gave higher radial thermal conductivities than the tangential ones for both softwood and hardwood species. The higher radial thermal conductivity predicted by the

models in softwood is due to the cell wall substance arrangement and earlywood-latewood arrangement. The high radial value for the hardwood species thermal conductivity is due to the ray contribution. Model predicted thermal conductivity values are similar for the two pine species. They both have a linear relationship with the LW% in the heat transfer direction for the tangential thermal conductivity, and an inverse relationship with $(1-LW\%)$ for the radial thermal conductivity. So the more latewood percentage there is in the samples, the higher the transverse thermal conductivity for the samples. The radial and tangential thermal conductivities both have a linear relationship with the MC in the range of 0% to 30% for all the three species. The radial thermal conductivity increases faster with the MC than the tangential thermal conductivity based on the model predictions. From the model predictions for softwoods in the whole MC range (from oven-dry to fully saturation), it was found that tangential thermal conductivity increased much more significantly with the MC when it is over the FSP. It became comparable to or even higher than the radial thermal conductivity. Over the FSP, free water began to appear in the cell lumen. This free water is responsible for the large increase in wood transverse thermal conductivity due to its much higher conductivity than the dead air in the cell lumen. No significant difference was found between radial and tangential thermal conductivities when MC is over FSP. The structure affect on the thermal conductivities in the two directions became less significant when free water takes part of the cell lumen.

Validation tests for the thermal conductivity models were performed on the oven-dry samples made from the three species. Examination on the correlation between the LW% and thermal conductivity measurements gave very good correlations between LW% and radial thermal conductivities but less good correlations between LW% and tangential thermal conductivities for softwood species. LW% in the testing samples was also shown to have a good correlation with the sample's specific gravity. And specific gravity has been used as the determining factor for the wood thermal conductivity for a long time. So the inclusion of LW% in the thermal conductivity models is approved of necessity. Thermal conductivity testing results from the two softwood species didn't show a significant difference between the radial and tangential directions as the model predicted. The hardwood species -- maple, showed the consistent difference between the two direction thermal conductivities in the tests. Models were re-examined to explain the discrepancy between the testing results and model estimations. Over idealization for the tangential models was discovered as the main reason for the significant discrepancy in the tangential results. An estimation factor should be applied to the tangential model estimated data in order to make up the loss by the models ideal assumption. Influence of

some uncertain input parameters on the model outputs was also discussed as the reason for the discrepancies. Sensitivity of the radial and tangential thermal conductivity with respect to the two input parameters' change were examined. Model estimated tangential thermal conductivity is sensitive to the k_a value (thermal conductivity of the dead air in the cell lumen), and the radial thermal conductivity estimates are sensitive to the thermal conductivity value of cell wall substance (k_c) for all the three species.

In the validation tests, thermal conductivities for the three species in the two transverse directions were also examined for the relationship with the temperature. Very good linear relationships were found for both directions of all the species, and explicit expressions were given for both thermal conductivities.

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