CHAPTER 4.

FINAL CONCLUSIONS AND RECOMMENDATIONS

4.1 Final conclusions

Geometric models for theoretically deriving the thermal conductivities in the radial and tangential directions of wood were developed in this project. The analogous electric circuit was employed to predict the effective thermal conductivities in the two wood anatomical directions (radial and tangential). The geometric model developed in this project improved previous models through its consideration of wood gross structure on the cross section and their interactions. The geometric models were based on the microscopic structure observation for wood and some macroscopic structure characteristics, such as earlywood-latewood interactions, and ray structure. The models were set up separately for softwood and hardwood species due to significant structure differences between the two types of wood.

Electron microscopic examination of anatomical structure was performed to provide the requirements for model development. The three species were chosen for the purpose of examining the softwood and hardwood differences. Two softwood species -- southern yellow pine and Scots pine, one hardwood species, soft maple, were examined and modeled. Cell wall percentages in the radial and tangential directions were measured using image analysis software and images of all three species taken using the Scanning Electron Microscopy (SEM). The structure of cell wall arrangement in the two directions were shown to be different. Some other special structure characters were measured, such as the ray percentage on the hardwood species' cross section. Statistical analysis were performed on the numerous microscopic measurements to eliminate subjective errors involved in the measurements. Cell wall percentage distributed in the radial and tangential directions was found to be statistically different for all the three species examined. Structure differences were only found between the softwood and hardwood (maple) species, but not between the two softwood pine species.

Geometric models for two types of wood (softwood and hardwood) and two directions (radial and tangential) were developed based on structure observations. Thermal resistance models transferred from the geometric models were used to predict effective thermal conductivity values in two directions. Models predicted higher thermal conductivity for the radial direction than the tangential direction. The higher radial thermal conductivity predicted by the model was due to the cell wall arrangement and earlywood-latewood arrangement differences in the two directions. The higher radial thermal conductivity predicted for the hardwood species was due to the rays on the cross section. The models gave a wide range of predictions for the thermal conductivities as a function of moisture content and latewood percentage within the wood. When the moisture content in wood is over the FSP, geometric models had to be modified to include the free water in the models to accurately predict the thermal conductivities.

Validation tests for the thermal conductivity geometric models were performed on ovendry samples specially made from boards. Experimental results didn't show significant difference between the radial and tangential thermal conductivities for the softwood species, but showed a consistent higher radial thermal conductivity for the hardwood species – maple. The higher radial thermal conductivity in maple was due to the significant amount of rays in the species. The insignificant difference between the radial and tangential thermal conductivity in softwood species was due to the similar structure and cell wall percentages in the two directions. Models predict good radial results for the thermal conductivities of all three species. Discrepancies were found between the theoretical values and experimental results for the tangential thermal conductivities. The analysis showed that the discrepancy was due to the idealization for the model-defined tangential direction in wood. Test analysis was conducted on the correlations between some structure-related parameters and the thermal conductivity results. Latewood percentage in the testing samples has very close correlations with the measured radial thermal conductivity. Specific gravity has been proved to have a determinant affect on the thermal conductivity values previously, and again demonstrated in this test. Based on the knowledge of wood and the definition of specific gravity, it is easy to infer that the cell wall amount in wood has a determinant effect on the specific gravity. Therefore, the geometric models based on the measured cell wall percent and measured earlywood-latewood percent should predict good thermal conductivity values for wood.

Sensitivity studies were done on a couple of uncertain parameters used in the model to examine the effects and contributions of these parameters to the model predictions. It was found that model estimated tangential thermal conductivity is sensitive to the value of thermal conductivity of the dead air in the cell lumen, and the estimated radial thermal conductivity is sensitive to the thermal conductivity value of cell wall substances.

With the wide range of thermal conductivity values provided by the geometric models, a two-dimensional transient, anisotropic heat conduction model for wood subjected to a heating process was developed. The model was solved by Finite Difference method programmed in *Mathematica* software.

Anisotropic material property influences on heat transport were investigated by a simulation run using the model with idealized geometry of southern yellow pine. The 3D graphs and contours plots for the temperature distributions in wood at each time step gave good visualization for the heat flow in the wood. Time series analysis based on the 2D transient temperature plots at certain points demonstrated faster heat flow in the radial direction of wood than in the tangential direction due to the higher radial thermal conductivity values predicted by the models. The external convective heat transfer coefficients were tested with different values to examine the effects. Spatial analysis based on the temperature distribution at certain planes showed higher temperature gradients near the surface area at the beginning of the heating process.

Validation tests for the 2D heat conduction model performed on blocks of three species were compared with model predictions to examine the capability of the 2D transient model to predict the heat transfer process in wood. It showed good predictions for the model developed in this study with use of the modified theoretical thermal conductivity values in the two practical transverse directions in wood. Sensitivity studies on the three parameters (h,k,and Cp) provided insight on how these parameters affect the temperature distributions inside wood and the relative importance to the industrial operation controls.

4.2 Recommendations

After struggling with some discrepancies found between the thermal conductivity theoretical values and experimental results, the author would recommend two efforts can be done in two directions. One is to modify the geometrical models for the tangential thermal conductivity derivation by considering the more practical structure on the macroscopic scale. The other one is to find an improved thermal conductivity measuring technique or equipment to be able to measure the small sized samples or even the microscopic scale measurement for the thermal conductivity. In the project's sensitivity study, it was found that the thermal conductivity value of the cell wall substance and the air within the cell lumen were important to the model estimations. The values for these two parameters now available were based on the testing results of more than 60 years old. New investigations or evaluation of these data need to be done.

The 2D transient heat conduction model is a possibly too simple for the complicated transport in wood with heat and mass always coupled together. Consideration for only the heat transfer in this project was to fulfill the purpose of examining only the anisotropic heat transfer properties' effects on the transport in wood and the reliability of using the theoretical estimations of the thermal conductivities from the geometric models developed in this study. *Mathematica* software was first introduced into the wood heat and mass transfer modeling area by this research. So the simplicity is always required at the start of a new technique being introduced. However, the mass transfer mechanisms should be considered simultaneously with the heat transfer mechanism in order to more precisely predict the temperature and other factors in wood for the drying industry. *Mathematica* has become a popular tool for engineering modeling due its dynamic, powerful results presentation and easy online publication. A 2D heat and mass transfer model solved and presented in *Mathematica* is recommended for future work.

Some small modification of the parameters used in the 2D model developed in this project have been pointed out after the analysis on the model output. For instance, the specific heat as a function of temperature should be modified in the current model in order to improve the model predictions. Thermal conductivity in the two transverse directions of a practical wood sample usually deviates from the true radial and tangential directions defined in the anatomical structures. Calculation of these two practical thermal conductivities in the transverse section was done in this project. But the calculated results were changing with the spatial locations on wood samples. Therefore the location dependence of the thermal conductivities should be considered in the future research.