A Numerical Model of Solar Transmittance for Isolated Trees in an Urban Area

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1 Introduction

Deciduous trees contribute to a more comfortable thermal environment by reducing the impact of solar radiation in summer and allowing more solar radiation in winter. These effects are influenced by tree geometry. Many studies on how leaves and branches affect the radiation interruption process (MONSHI & SAEKI, 2005; TALBOT & DUPRAZ, 2012) have been conducted; however, little is known about the difference in effects produced by the various tree species used for urban landscaping in Japan. This paper discusses the solar shading effects of an isolated tree and presents a numerical analysis using a computer graphics (CG) tree model.

2 Material and Methods

2.1 Model description

Simple solar shading models are useful as simulation tools to predict the thermal environment in outdoor living spaces. Our target users are landscape designers, architects, and urban planners who need to compare tree species when designing outdoor urban living spaces where various solar and reflected incident angle radiation beams must be considered. This paper defines ratio of direct solar radiation reaches on the tree shade by simulating of a ray-tracing method as solar transmittance. Simulation models of solar shading are related by the tree canopy structure and solar transmittance depending on tree geometries (KUMAKURA et al., 2011). A method for describing the solar transmittance of inhomogeneous canopy structures using Leaf Area Index, G-function, and a Clumping Index that uses Poisson distribution, has been proposed (NILSON, 1971). On the basis of on this methodology, Talbot et al. suggested a formula that also considers the Branch Area Index for an isolated tree, and we have based our model for predicting solar shading effects in summer and winter on this formula. Figure 1 shows our formula and the relationship between tree geometries and design simple parameters, such as tree species, crown shape and leaf density. We have added three parameters to the formula suggested by Talbot et al. to describe various tree crown shapes and changes in leaf density. The added parameters facilitate two new functions. One is the new overlapping coefficient function, which shows the relationship between leaves and branches and is dependent on branch structure and leaf density. The other is the new Clumping Index, which is dependent on crown shape and shows the complexity of the layered structure. From the computer graphics (CG) tree models, we determined the coefficient to calculate the solar transmittance by incident angle for each species.

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2.2 CG tree model

De Reffye et al. found a correlation between the architectural model and measurements from actual trees. Their method could make CG tree model for various tree species (DE REFFYE et al., 1988, natFX, Bionatics). Therefore, we chose their model to represent actual tree geometry. Five tree species were constructed (*Ginkgo biloba*, *Zelkova serrata*, *Liquidambar styraciflua*, *Platanus orientalis*, *Prunus yedoensis*) using CG software. These species are all used in urban landscaping in Tokyo, and five models of each species were constructed using a random seed parameter to consider differences in leaf density.

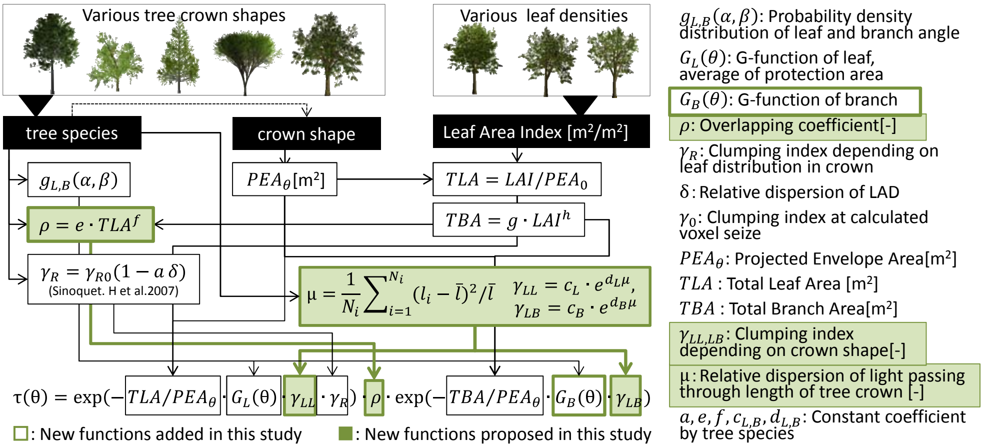

Fig. 1: Calculation process of solar transmittance by incident angle using CG tree

2.3 Modeling of solar transmittance

Using CG tree models, new parameters are formulated on the basis of numerical analysis using a regressive approach. Other parameters are obtained from a previously reported method that used CG geometry (SINOQUET et al., 2007; KUMAKURA et al., 2011). The new overlapping coefficient function is formulated in terms of total leaf area for each species. The new Clumping Index is formulated by the relative dispersion of light passing through the length of the tree crown. Using the new added parameters, our proposed solar transmittance formula more clearly shows the difference among tree species. We used the RMSE (root-mean square error) to check the accuracy by comparing projection images that were created by a ray-tracing method (KUMAKURA et al., 2011). Figure 2 shows the influence of the added parameters on the accuracy of solar transmittance for each species. *Ginkgo biloba*, which is characterized by low density and random distribution geometric features, is more influenced by branch angle G_B than leaf density. *Liquidambar styraciflua*, which is characterized by high density and clumping distribution geometric features, is more influenced by the Clumping Indexγ_{LL}, γ_R than the branch angle. *Prunus yedoensis*, which has a complex crown shape, is influenced by the new Clumping Index $\gamma_{LL,\ LB}$. *Platanus orientalis*, which has a large area per leaf, is influenced by the overlapping coefficient functionρ. In *Zelkova serrate*, the leaf layer and branch layer are clearly separated, and consequently this specie is influenced by both branch angle G_B and the new Clumping Index$\gamma_{LL,\ LB}$. These results show that our proposed model make it possible to compare seasonal change and leaf density in the summer season by species.

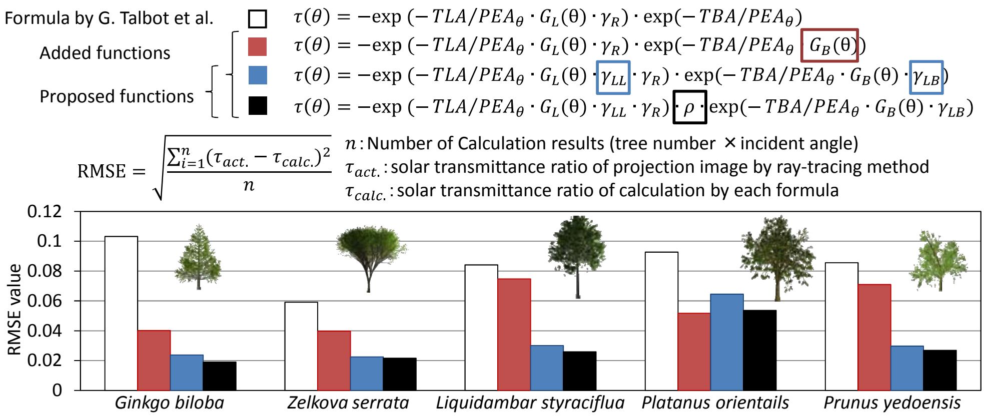

Fig. 2: Influence of added parameters on accuracy of the solar transmittance by species

3 Simulation Application

The tree shapes representing tree species were modeled using 3D CAD. The solar transmittance data by incident angle were calculated by the process shown in Figure 1. Using these solar shading models of tree crowns, we proposed an urban greenery plan that takes solar shading effects in an actual open space into consideration (Figure 3).

We used a numerical simulation system (ASAWA et al., 2008) to evaluate the effects of spatial forms and building materials on an outdoor thermal environment. Our calculations involved a comparison of the effects of these tree species on the thermal environment in summer and winter. Figure 3 shows a perspective depiction of the surface temperature distributions at 12:00 for both summer and winter. The surface temperatures in the shaded areas were calculated to be between 35 °C and 45 °C in summer and 22°C and 28 °C in winter. The values varied depending on tree crown shapes and the solar transmittance. The graph in Figure 3 shows a comparison of the differences of simulated incident solar radiation with and without a tree (0.6 m above the ground, i.e., sitting position under the tree). *Liquidambar styraciflua* and *Zelkova serrata* showed the highest incident solar radiation in summer and winter, respectively. These results show that this tree model can simulate the effects of tree species and leaf status on solar shading in both summer and winter.

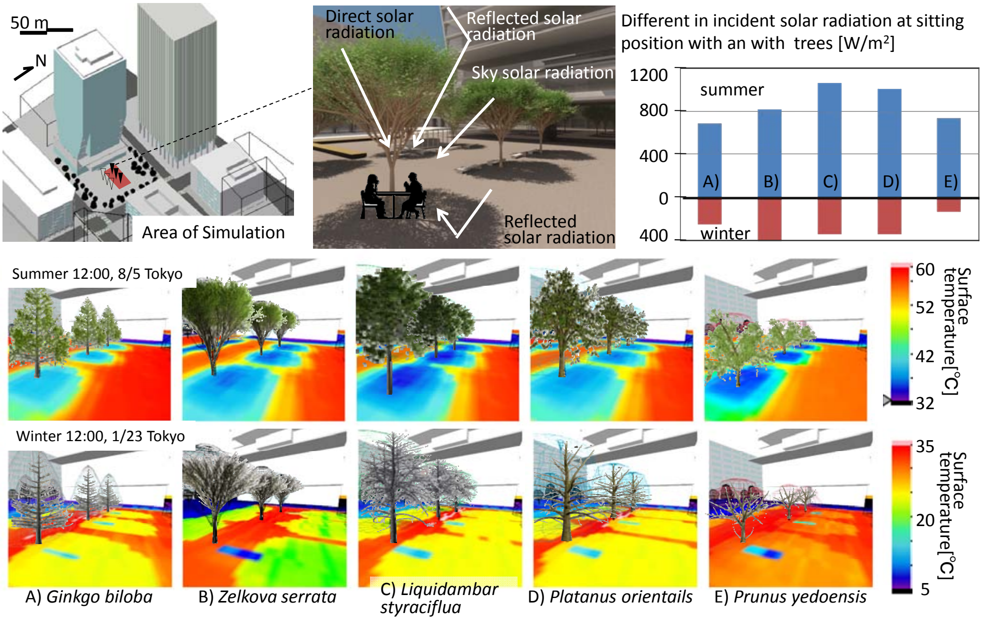

Fig. 3: Surface temperature distribution in the tree shadow

4 Conclusions

This paper has reported the development of a new numerical model that uses overlapping coefficient and improved Clumping Index functions to predict thermal effects caused by the solar shading of a tree in an urban area. On the basis of the results, the differences in solar shading effects of various isolated trees on the thermal environment in an actual urban area can be predicted using a 3D CAD compatible thermal environment simulator. The calculations provide some evidence that different tree species, represented by crown shape and solar transmittance, affect shaded surface temperatures in both summer and winter differently.

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