The Effects of Windbreak Forests on the Summer Thermal Environment in a Residence

Jiang He*1 and Akira Hoyano2

1 Fellow, Project Researcher, Interdisciplinary Graduate School, Tokyo Institute of Technology, Japan
2 Professor, Interdisciplinary Graduate School, Tokyo Institute of Technology, Japan

Abstract
As urbanization progresses, the outdoor thermal environment is deteriorating due to the decrease of vegetation and increase of constructed surfaces. Environmental problems such as the heat island phenomenon occur not only in large cities but also in mid-sized and small cities. Increasing tree or vegetation plantings is one of the most effective strategies to mitigate environmental problems and create a comfortable living environment. In this study, the microclimatic effect of a windbreak forest surrounding a residence was analyzed based on field measurements and numerical simulation results. Spherical thermographs of surface temperature distribution observed in an actual residence were used to identify the thermal effect of the windbreak forest and surface materials. A coupled numerical simulation method of computational fluid dynamics (CFD) and outdoor thermal simulation was used to evaluate the microclimate and thermal comfort in outdoor living spaces. The proposed simulation method was validated by comparing the simulated results with the measurement data. In addition, the residence was modeled using the coupled simulation program to quantify the microclimate and outdoor thermal comfort. Simulation results show that this simulation method is capable of predicting the solar shading effect and wind speed reduction due to trees as well as thermal improvement from decreased ambient air temperature and surface temperature.

Keywords: windbreak forest; residence; microclimate; thermal comfort; field measurement; coupled simulation

1. Introduction
A long time ago, trees were planted around the irregularly spaced traditional houses (see Fig.1) on the Tonami plain in Toyama prefecture in Japan. Besides the winter windbreak effect, these trees (collectively called a windbreak forest) have a solar shading effect from their crowns in summer. However, in recent years, residences with a windbreak forest are disappearing due to urbanization and inadequate tree care. Compared to residences with a windbreak forest, the outdoor thermal environment in newly built residential areas is worsening due to the decrease of vegetation and increase of constructed surfaces such as concrete walls and pavements. From the viewpoint of the thermal environment, it is beneficial to protect windbreak forests from further decline. On the other hand, as a bioclimatic design to create a comfortable living environment from better use of windbreak forests, it is required to predict and evaluate the microclimatic and thermal effects of trees or vegetation and employ well-informed strategies at the design stage.

As described in many previous studies (Shashua et al., 2000, Simpson, 2002, Dimoudi and Nikolopoulos, 2003), it is already well understood that trees have a microclimatic effect on the reduction of outdoor air temperature, a thermal effect on reducing surface temperatures of tree-shaded surfaces, and an energy-saving effect on building cooling. For evaluating these effects under various conditions (tree characteristics, building orientation, ground cover materials, etc.), simulation methods have become a necessary and practical alternative.

The first part of this paper describes the solar shading effect of a windbreak forest in an actual residence from field measurements conducted on a sunny summer day. The second part of the paper presents a coupled simulation method for predicting the microclimatic effect of a windbreak forest and outdoor thermal comfort in outdoor living spaces. In order to validate the simulated results, a comparison was carried out using measurement data. As a case study, simulations were performed to evaluate the summer microclimate and outdoor thermal comfort in the test residence. Spatial distributions of external surface temperature, airflow, MRT (mean radiant temperature) and SET* (new standard effective temperature) in the outdoor spaces were discussed based on the simulated results.

*Contact Author: Jiang He, Fellow, Project Researcher, Interdisciplinary Graduate School, Tokyo Institute of Technology, 4259-G5-2 Nagatsuta-cho, Midori-ku, Yokohama, 226-8502 Japan
Tel: +81-45-924-5510 Fax: +81-45-924-5553
E-mail: kakohe.j.aa@m.titech.ac.jp
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2. Methodology

2.1 Field measurement

In order to understand the actual microclimate in a residence surrounded with a windbreak forest, field measurements were conducted in a traditional Japanese residence located in Tonami (Fig.1.). This paper focuses on describing the measurement data obtained in a residence with a windbreak forest where windbreak trees at a height of 15 m or so are densely planted (Fig.3.). We measured air temperature, relative humidity, wind speed and solar radiation at a height of 1.2 m in outdoor living spaces of the test residence. For collecting local weather data, ambient air temperature, relative humidity, wind speed, wind direction and total horizontal solar radiation were continuously measured at a location (1.2 m height above the ground) near the residence.

Surface temperature distribution was measured with the spherical thermograph system developed by our laboratory (Asano and Hoyano, 1998). A photo of the spherical thermograph system is shown in Fig.2., and the specifications are listed in Table 1. Descriptions of other instruments are summarized in Table 2.

The field measurements were conducted in July and August 2001. Measurement data collected on sunny days were used for analysis.

2.2 Numerical simulation

In order to predict the microclimate in the residence, it is necessary to simulate air temperature, airflow and surface temperature distributions around the buildings. Many microclimate simulation models have been developed in previous studies5-9). However, in these previous studies, spatial forms and construction materials of buildings were simplified. In reality, outdoor environments are composed of trees and buildings, and other structures that have complicated spatial forms and are made of various materials. It is well known that spatial forms and construction materials affect formation of the outdoor microclimate. Moreover, the simulation methods used in these previous studies were not developed as a design tool for designers, and so there was no tool to integrate into a 3D-CAD system to reproduce spatial forms of buildings and other structures in detail.

As a computer-aided design support tool to predict an outdoor microclimate, we developed a numerical simulation method by coupling a computation fluid dynamics (CFD) simulation with the 3D CAD-based simulator previously developed by our research group (Asawa et al., 2008). This coupled simulation method was used to evaluate the microclimate and thermal comfort in outdoor spaces of the test residence.

3. Analysis of Measurement Results

Fig.6. shows six spherical thermographs observed...
Fig. 3. East View of the Test Residence

Fig. 4. Plan of the Residence and Measurement Locations

Fig. 5. Spherical Views from Measurement Locations (a)-(c) Indicated in Fig. 4.

Fig. 6. Spherical Thermographs Taken at Measurement Locations (a)-(f) Indicated in Fig. 4.
at six locations (a-f) (see Fig.4.) in the residence. Spherical views around these locations are provided in Fig.5. The residence consists of a house and four barns. Tall trees at a height of 15 m are planted around the house. The approach from the entrance to the house is paved with concrete. Near the entrance is a wet field and a lawn is on the west side of the house.

The measurement day was a sunny summer day (July 28, 2001) with low wind. Wind speeds during the daytime were approximately 3 m/s outside the residence. From thermograph (a) in Fig.6., taken in the late morning (11:30), it can be seen that the surfaces with a higher temperature are the ground and building surfaces; these were not in the shade, and so they received direct solar radiation. Horizontal solar radiation received at the measurement location was 432 W/m², which was more than half of total horizontal solar radiation. Surface temperatures of the tree crown and shaded ground were approximately equal to air temperature. The temperature difference between the shaded and un-shaded ground (or building) surfaces was more than 5°C. At noon, surface temperatures of the ceiling were 3-5°C higher than air temperature due to solar heat transferred from the eaves and roof (see thermograph (b) in Fig.6.). Surface temperatures of the floor were approximately 3°C lower than air temperature. Internal wall surfaces were slightly cooler than air temperature.

As seen from thermograph (c-d) in Fig.6., most of the south courtyard was in the shade of trees, and surface temperatures of their surroundings were as low as air temperature. Surface temperatures of the tree-shaded ground covered with wet soil were 2-3°C lower than air temperature.

It can obviously be seen from thermograph (e) in Fig.6. that part of the west-facing walls was irradiated by direct solar radiation, and so these surface temperatures were several degrees higher than air temperature in the afternoon. Most of the west-facing walls was shaded by trees and had a surface temperature which was nearly equal to air temperature. It was also found that surface temperatures for the tree-shaded ground covered with wet soil were about 2°C lower than air temperature. In the late afternoon, although part of the west-facing walls was irradiated by solar transmittance radiation passing through trees, internal surfaces in the west rooms were kept 1-2°C lower than air temperature (see thermograph (f)).

From the measured data indicated at the bottom of each thermograph in Fig.6., it can be seen that air temperature varied little during the daytime, and wind speeds were below 1.5 m/s in outdoor living spaces of the residence.

4. Simulation Methodology

4.1 Coupled simulation method

The coupled simulation consists of the following two simulation subsystems: (1) outdoor thermal simulation, (2) CFD simulation. Each subsystem can be independently performed and the simulated results of one subsystem can be used as input data for the other subsystem. The process of the coupled simulation is outlined in Fig.7. The first step is to create 3D-CAD models for buildings, trees and other structures in the area. The 3D-CAD models are created in the same way as in a general architectural design. The same 3D-CAD models are used for each simulation subsystem.

The second step is to perform a CFD simulation under a steady-state and constant-temperature condition. From the CFD simulation, airflow distribution data around the external surfaces are used as boundary conditions to perform the outdoor thermal simulation. From the outdoor thermal simulation, calculated temperatures of external surfaces are output and used as boundary conditions for the second CFD simulation, in which spatial distributions of air temperature, air velocity, etc., are calculated. The CFD simulation is performed under the condition that all windows are closed.

Simulated results such as air temperature, air velocity, external surface temperature distribution, etc., throughout the day are obtained. From simulated results of surface temperatures, the mean radiant temperature (MRT) can be estimated by the equation below (Nakaohkubo and Hoyano, 2008). In the calculation of the MRT, the influence of solar radiation including reflected radiation is considered, and a human is considered as a micro-tube with six faces (Nakamura, 1987).

\[
MRT = \left(\frac{a_1 \sum S_i I_s + \sum W_j (I_{s0} + I_{s1})) + \sum W_j I_{s2}}{\sigma}\right)^\frac{1}{2} - 273.15
\]

In the above equation, \(a_1\) is solar absorptance for the human, \(S_i\) is effective radiation area of the human (m²), \(S_i\) is surface area of the human body (m²). \(I_s\) is direct solar radiation (W/m²). \(W_i\) is weighting factor for face \(i\). \(I_{s0}\), \(I_{s1}\), and \(I_{s2}\) are sky solar radiation, reflected solar radiation and total long-wavelength radiation (W/m²), respectively, irradiated on face \(i\). \(\sigma\) is Stefan-Boltzman constant.
constant (W/m² K²). \( i \) is face number of the micro-tube.

A thermal sensation index, called new standard effective temperature (SET*), can also be estimated. SET* represents the degree of a human's thermal comfort depending on the state of the following six variables: air temperature, air velocity, mean radiant temperature, relative humidity, and activity level of an occupant and his or her clothing insulation. In this study, SET* was calculated by the program based on the human body heat balance model proposed by Gagge et al. (1986).

### 4.2 CFD simulation

Commercial CFD software (STREAM) was used in the airflow simulation. Three-dimensional turbulent airflow was given by Reynolds averaged Navier-Stokes equations (RANS). The turbulence model was an improved \( k-\varepsilon \) model (ANK model), which tends to improve overestimation of turbulent kinetic energy around windward corners, etc. The governing equations were solved with SIMPLE algorithm. A numerical scheme (QUICK) was used for pressure correction in solving the governing equations. The calculation for humidity distribution was not performed in the CFD simulation. The reason for this is that little difference in absolute humidity between the residences with and without a windbreak forest was found from the field measurement results (Matsui et al., 2002).

Air resistance, turbulence generation and dissipation around trees were taken into account by applying a canopy model (Yamada, 1982) to the \( k-\varepsilon \) equations. Leaf area density was considered to be average: the value used in the simulation was 4.5 m²/m². The drag coefficient of a tree was assumed to be 0.6.

As inflow conditions, the law of exponents was applied to the vertical distribution of wind velocity and turbulent energy. The inflow conditions were input based on the measured wind velocity at a height of 1.2 m above the ground. The dissipation ratio of turbulence was calculated on the assumption that the generated and dissipated turbulences are balanced. Other boundary conditions and the CFD simulation model are shown in Table 3, and Fig.8., respectively.

### 4.3 Outdoor thermal simulation

The outdoor thermal simulation was performed using the 3D-CAD models shown in Fig.9. for buildings, trees and other structures in the residence. Three-dimensional spatial forms of the buildings, trees, etc., and two-dimensional ground surfaces were divided into mesh grids, and thermophysical data of construction materials, such as albedo and conductivity and solar transmittance, was assigned to the grids. A uniform mesh size (resolution) of 0.4 m was used in the simulation. The external surface temperature for each mesh can be determined by solving a non-steady-state one-dimensional heat balance equation in normal to the surface. In the heat balance equation, three-dimensional radiation irradiated on the surface was taken into account. The short-wavelength radiation on the surface was direct solar insolation, sky solar radiation and reflected solar radiation. Reflected solar radiation includes both specular reflection and isotropic diffuse reflection. Only the first reflected solar radiation was considered in the calculation. Atmospheric radiation and long-wavelength radiation from the surroundings were considered as the long-wavelength radiation irradiated on the surface. Sky solar radiation and atmospheric radiation were calculated from the sky view factor for each mesh. The surface convection coefficient was considered to be a function of air velocity and given by Jurges' equation (Jurges, 1924).

The non-steady-state one-dimensional heat conduction equation for each mesh was solved by using the above-mentioned heat balance data as boundary conditions for external surfaces. Boundary conditions for internal surfaces were indoor air temperature for the buildings and underground temperature for the ground. Rooms on a floor were considered to be a single room without partition walls, and indoor air temperature was uniformly distributed at an analyzing time.

The tree shape was modeled as a 3D-CAD model and the crown was composed of meshes containing solar transmittance data. Solar transmission radiation decreased as it passed through the tree mesh model. This mesh model makes it possible to quantify the influences of the position and distance of the rays within the crown on the solar transmission. The surface temperature of a tree's crown or lawn was calculated by empirical formulas derived from the experimental data and can be expressed as a function of solar radiation irradiated on the surface, ambient air temperature, and air velocity (Shimokawa et al., 1996, Hoyano, 1983).

The backward-difference method was used for solving the non-steady-state heat conduction equation. One simulation was run using 5-day weather data at 5-minute time steps in order to obtain a periodic steady-state solution. Simulated results of surface temperatures for the 5th day were output and used for analysis. A detailed description of the simulation methodology can be found in Asawa et al. (2008).

#### 4.4 Input data

Weather data measured at a location (1.2 m height above the ground) near the residence was used as input weather conditions for the simulation. The
measurement location and measured weather data for a sunny summer day (August 2, 2001) are shown in Fig.10. and Fig.11., respectively. The sky was clear through the day. The maximum of total horizontal solar radiation reached 900 W/m². The minimum and maximum of ambient air temperature for the day were 26°C and 32°C, respectively. Wind speeds were 1.5-3.0 m/s and below 1.0 m/s for the daytime and nighttime period, respectively. From the measurement result that west and southwest wind prevailed during the day, inflow directions were set to be the west in the CFD simulation.

Table 4. shows cross sections of the roof and wall for the house and thermal properties for the outdoor thermal simulation. The values of conductivity and specific heat in Table 4. were provided from reference 19 (AIJ, 1991).

5. Simulation Results and Discussions

The simulated results at three different times are used in the following sections. 12:00 is the time at which the solar altitude is the maximum and the shadow on the ground is the minimum. 15:00 is the time at which insolation on the vertical (wall) surface is the maximum. 20:00 is the time at which the heat-storing effect of the ground or constructed surfaces is most obvious.

5.1 Validation of the proposed simulation method

In order to validate the proposed simulation method, we carried out a comparison between simulated and measured air temperature. Fig.12. presents air temperatures measured at measurement location (c) (see Fig.4) and simulated air temperatures at three times (12:00, 15:00, 20:00). A simulated air temperature is the average for the area (4 m × 4 m) around the measurement location (at a height of 1.2 m above the ground). As shown in Fig.12., the simulated results agree well with the measured data.

5.2 Surface temperature distribution

Simulated results of surface temperature distribution for the three hours are illustrated in Fig.13. As seen in the left thermograph of Fig.13., most of the ground was in the shade of trees at noon. Surface temperatures of the shaded pavement were approximately 15°C lower than that for the un-shaded pavement. It can be found that most of the west-facing walls was shaded by trees at 15:00 (see the middle thermograph in Fig.13.). As a result, the shaded wall surfaces were as cool as the ambient air and their temperatures were approximately 10°C lower than the un-shaded walls. Ambient air temperature mentioned here is the air temperature taken at the measurement location near the residence.

As seen from the right thermograph in Fig.13., nighttime surface temperatures of the ground covered with wet soil or lawn were as low as ambient air temperature, whereas nighttime surface temperatures of the concrete-paved ground were 3°C higher than ambient air temperature due to stored heat from solar radiation received during the daytime.
From surface temperature distributions, it can also be seen that most of the ground was wet soil or lawn and in the shade during the daytime. These surface temperatures were nearly equal to or slightly lower than ambient air temperature. The same results were found in the field measurements as mentioned above.

5.3 Air temperature and wind velocity distribution

Fig. 14. (A) shows air temperature distribution at the Y-Y’ cross section indicated in the middle thermograph of Fig. 13. and air velocity distribution at a horizontal level above the ground. At 15:00, wind was blowing from the west and the inflow velocity was approximately 1.5 m/s at a height of 1.2 m. Air velocity on the windward and leeward sides of the house was reduced to 0.5 m/s due to the trees’ wind reducing effect.

Fig. 8. CFD Simulation Model
Fig. 9. 3D-CAD Model of the Residence
Fig. 13. Simulation Results of Surface Temperature Distribution at 12:00, 15:00, 20:00 on a Sunny Summer Day
Fig. 14. Simulation Results of Air Temperature, Velocity, MRT and SET* Distribution.
   (A): Air temperature and velocity distribution at Section Y-Y’ (top), at 1.2 m height (bottom).
   (B) and (C) show MRT distribution at 1.2 m height at 15:00 and 20:00, respectively.
   (D) shows SET* distribution at a height of 1.2 m above the ground at 15:00.
Although air temperature above the concrete-paved ground was slightly higher than ambient air temperature, air temperature in most of the outdoor living spaces was nearly equal to ambient air temperature.

5.4 MRT and SET* distribution

Simulated results of MRT distribution at a height of 1.2 m at 15:00 are shown in Fig.14.(B). The MRTs in the shaded areas were 15°C lower than those in the un-shaded areas. As shown in Fig.14.(C), nighttime MRTs under the trees were as low as ambient air temperature due to the shading effect of the trees on radiation cooling from the ground to the sky. Nevertheless, nighttime MRTs in most of the outdoor living spaces were 1-2°C lower than ambient air temperature.

We calculated SET* values at a height of 1.2 m on the assumption that the metabolism and clothing of a human, wearing a short-sleeved shirt and trousers and slowly walking or standing, were 1.5 met and 0.5 clo, respectively. Relative humidity used in the calculation of SET* was given from the measured data.

Calculated results for 15:00 are shown in Fig.14.(D). The maximum SET* was found at locations above the pavement on the leeward side (east of the residence). The SET* values for the shaded and un-shaded spaces were within 30-35°C and 36-40°C, respectively. The SET* values for the open spaces on the east side of the house or above the pavement near the entrance were higher than those for the other locations. The reason for this is that air velocity was reduced in these spaces due to the trees’ windbreaking effect (because the SET* increases with the decrease of wind speed).

6. Conclusions

To clarify the actual summer microclimate in outdoor spaces of a residence with a windbreak forest, field measurements were conducted. Numerical simulations were also performed to predict the microclimate and thermal comfort in the outdoor spaces of the residence by using a coupled method of CFD and outdoor thermal simulation. The results obtained in this paper are summarized as follows.

The field measurement results show that surface temperatures in the tree-shaded spaces were near ambient air temperature on a sunny summer day. Surface temperatures of the shaded ground covered with wet soil or lawn were about 2°C lower than ambient air temperature.

In order to evaluate the microclimate and outdoor thermal comfort, a coupled simulation method of CFD and outdoor thermal simulation was used, and this proposed method was validated by comparing the simulated results with the measurement data.

The residence was modeled using the coupled simulation program to quantify the microclimate and outdoor thermal comfort in terms of surface temperature, air temperature, air velocity, MRT and SET*. Through simulations it was found that the proposed simulation method is able to predict and quantify the solar shading effect and wind speed reduction due to trees, as well as the thermal improvement from reductions of ambient air temperature and surface temperature.

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