Development of support tool for outdoor thermal environmental design of urban/ building using numerical analysis

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ABSTRACT

The purpose of this study is to develop a thermal design tool for architectural designer by combining a heat balance simulation for urban surfaces, including buildings, the ground and greenery, with a 3D-CAD. This tool is constructed by improving the previous simulation model, which uses the Geographic Information System for the input data. The simulation algorithm is improved so as to predict the surface temperature distribution of urban blocks while taking into account the actual design of the outdoor space using the 3D-CAD system. A pre-post processing system using all-purpose 3D-CAD software is developed. The results obtained by applying this simulation tool to an area of detached houses reveals that the tool is able to simulate the effects of building shape, materials, and tree shade on the surface temperature distribution, as well as the MRT and HIP, which are evaluation indexes of the urban thermal environment.

KEYWORDS

Thermal environment, Surface temperature,Environm ental design tool, Numerical simulation, 3D-CAD

1. INTRODUCTION

Urban Heat Island Phenomena is an urban environmental problem that is attracting public attention in Japan. Under such circumstances, the central government of Japan adopted the Heat Island Countermeasure Scheme in March of 2004. Consequently, both the central government and local governments are now considering the introduction of heat island mitigation policies when promoting urban regeneration. Urban development and building design considering the urban thermal environment has become of interest. Architectural designers would then be able to evaluate proposed designs on not only the architectural design, but also on the design's thermal impact.

In recent years, the availability of numerical simulation tools for evaluating the urban thermal environment that can be implemented using personal computers has increased gradually. For example, ENVI-met (Bruse M, Fleer H. 1998)(Anon), provided as freeware on the web, is a three-dimensional microclimate model, based on computational fluid dynamics (CFD), designed to simulate micro scale interactions between urban surfaces, vegetation and the atmosphere in an urban environment.

In the present study, we develop a thermal design tool for use in planning outdoor spaces by combining a heat balance simulation for urban surfaces, including buildings, the ground and greenery, with a 3D-CAD system implemented on a personal computer.

2. OUTLINE OF SIMULATION TOOL DEVELOPMENT THAT INCORPORATES A 3D-CAD SYSTEM

2.1 Concepts of the support tool

The three followings are important features of developing the thermal design tool of thermal environment for architectural designers.

i) The simulation tool allow to predict a thermal influence of the buildings designed by designers

An outdoor surface temperature is dependent upon spatial forms and materials such as outdoor object shapes, building and ground materials and a tree's crown. If the tool allows to reproduce the outdoor spatial forms and to predict thermal impact, Designers are able to evaluate proposed designs on not only the architectural design, but also on the design's thermal impact.

ii) The input and pre-processing method using the 3D-CAD system and the GUI.

It is important to build the interface for designer in order to integrate environmental simulations into architectural design and urban planning in practical business, at present, no environmental design tools that use 3D-CAD systems. The input and pre-processing method using the 3D-CAD system is developed. It can connect the design parameters such as building shape, material, tree, and the calculation parameters of heat transfer analysis such as coefficient of thermal conductivity and volumetrically specific heat

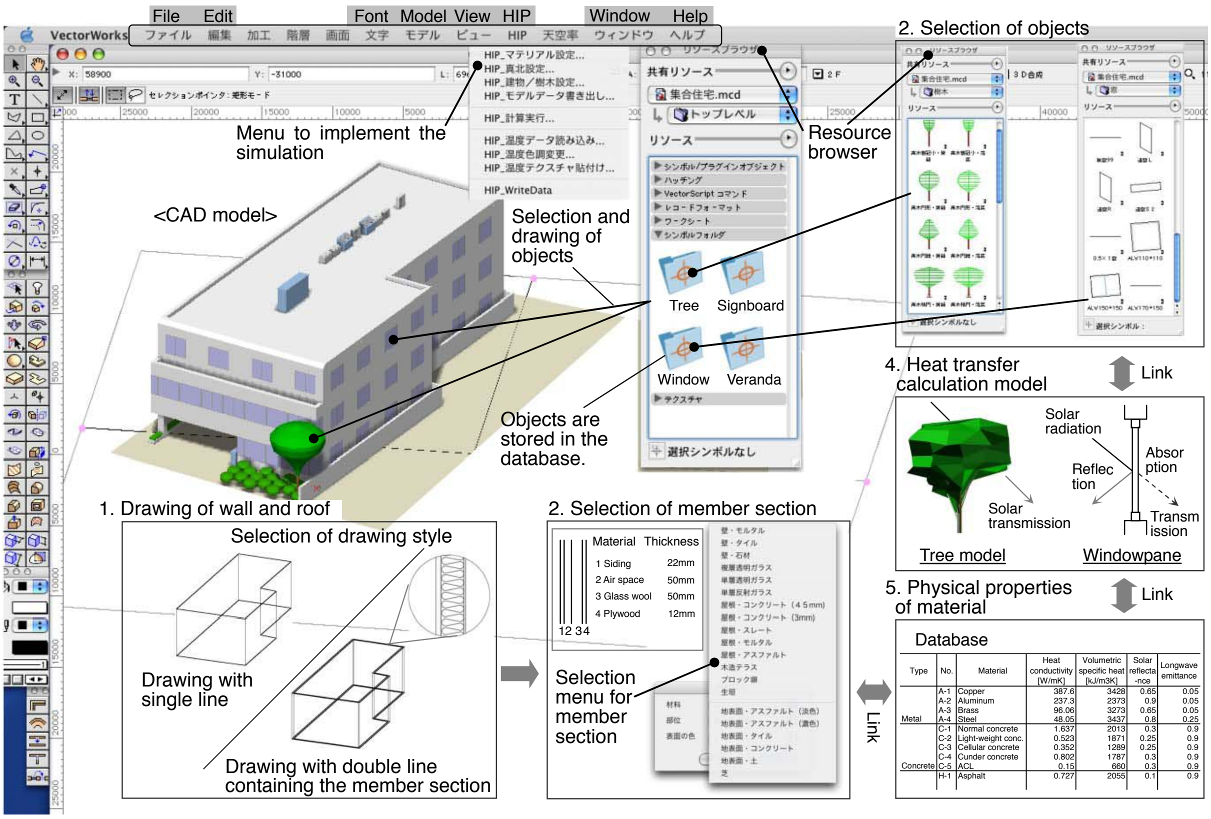


Figure.1 Input and pre-processing method using the CAD software interface

iii) Visually expressing the results of the calculations This allow the designer to understand and evaluate the effects of spatial forms and materials on the outdoor surface temperature.

2.2. Assessment of the requirements for development of the simulation system

This simulation model is mainly constructed by heat transfer calculation models, which are generally used for thermal environment simulations, following the fundamental formula of surface heat balance. The fundamental algorithm of this simulation model was then constructed in the previous study (Iino A, Hoyano A. 1998) by the authors group, using measured data obtained by airborne remote sensing, so that the present paper focuses on the following two important aspects. One is the simulation algorithm to realize the heat balance calculation in an outdoor space having a detailed spatial geometry, and the other is an integration method of heat balance simulation with a 3D-CAD system for use as a practical tool. The prediction of local air temperature and humidity will be considered in a future study, whereas the present study deals with the prediction of the surface temperature distribution.

In the previous simulation model (Iino A, Hoyano A. 1998), the building geometry is simply modeled by entering the building height information into the 2D-plan data derived from GIS data. In addition, input and output processes are based on manual operation, depending on the experience and specialty of the user. In order to improve the previous system to predict the surface temperature distribution using the all-purpose 3D-CAD, the following features should be examined in developing the simulation tool:

(1) The input and pre-processing method using the CAD system and the GUI.

(2)The database linking the design parameters and the parameters for the heat transfer calculation

(3) The simulation algorithm is improved to further reduce the calculation time and PC memory required for the simulation, allowing the system to be run on a personal computer.

(4) Establishment of the simulation parameters and the system

(5) A method for visually expressing the results of the calculations via 3D-CAD.

3. INTEGRATION OF THE SIMULATION MODEL WITH THE 3D-CAD SYSTEM

3.1. Input and pre-processing method using the 3D-CAD system

In order to develop a simulation tool for designers, the input and pre-processing method of this tool are developed using the features of the CAD system and the GUI. Figure 1 illustrates the input and pre-processing method using the CAD software interface. Buildings and trees are drawn using 3D objects. The drawing line style is selected as either single line or double line containing the building member section. The important parameters for reproducing the shapes of trees are height, width, crown shape, and height under the crown. Ground cover is drawn using 2D objects. Users can input or select component materials and building members, such as walls, roofs and veranda, with the aid of various dialog boxes and databases.

The following data are stored in the "Spatial Component Database": (a) Buildings: building structures, building members, and component materials (b) Trees: species (c) Ground: ground cover and its inner component.

The parameters for the heat transfer calculation, including the physical properties of materials and the heat transfer calculation models, are then automatically selected and determined from the aforementioned parameters and the following databases. The physical properties of materials are stored in a "Material Database". Objects that require specific modeling of heat transfer, for example rooftop lawns and water-permeable pavement, are also included in the “Heat Transfer Calculation Model Database”.

3.2. Method of generating the 3D-mesh model for calculation

The CAD models generated by the above process are then transformed into a 3D-voxel mesh model that includes the calculation parameters required for heat transfer analysis. Figure 2 illustrates a schematic diagram of the conversion method. The 3D-CAD model is sectioned horizontally at a certain height, and a horizontal section of the CAD model is then generated. The 2D figure data of the section is then transformed into mesh data. This process is repeated automatically from the bottom to the top of the CAD model at an interval of the mesh size. Consequently, the 3D-voxel mesh model is completed. The calculation point is set for all of the meshes, and the calculation parameters (component materials, normal direction of the mesh surface, etc.) input during the aforementioned process are automatically stored in the 3D-mesh model. Tree mesh models are also generated by the same process.

3.3. Heat balance calculation method reproducing spatial geometry

The heat balance calculation for predicting the surface temperature of each mesh is performed as described below. In the developed calculation method, the heat balance on the external surfaces is simulated using a high-resolution voxel mesh model generated by the above method. The applied mesh size is determined in Section 4.2. Figure 3 shows a schematic illustration

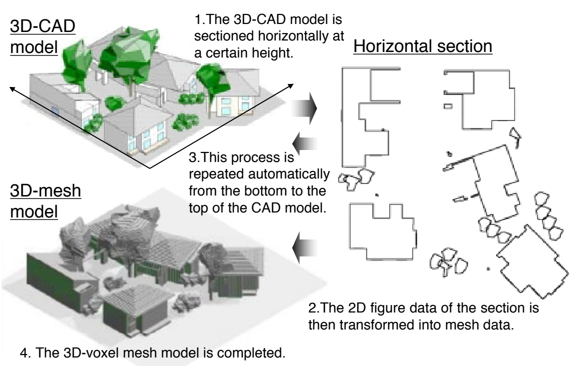


Figure.2 Schimatic diagram of the mesh model generation

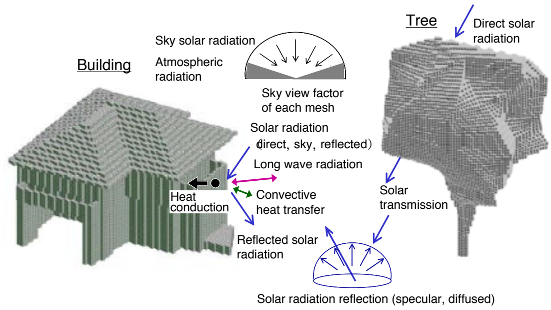


Figure.3 Schematic diagram of the heat balance calculation method

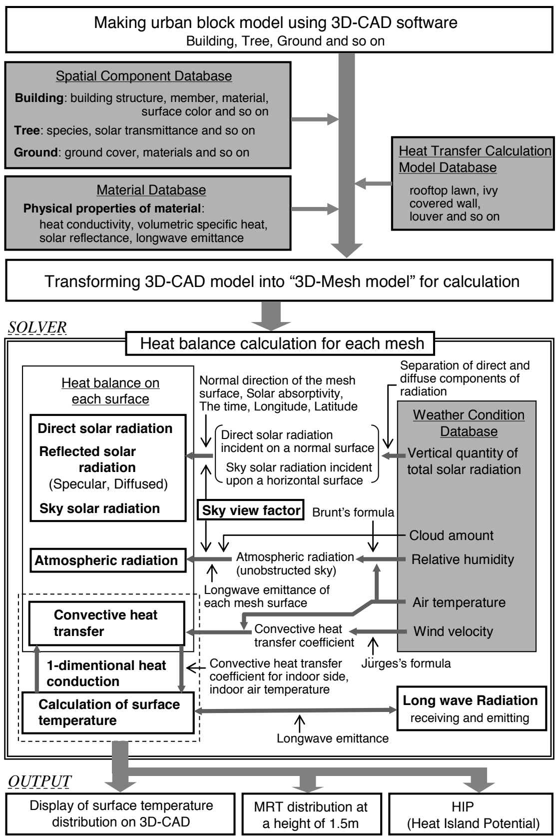


Figure.4 The flow chart of this simulation tool

of the mesh models and the heat balance calculation method. Figure 4 shows a flow chart depicting the various components and processes involved in this tool. The fundamental formula of the heat balance calculation is shown in the following formula (1):

$$q = a_{su}\left(cos\theta \cdot I_{DR} + \Phi_{sky} I_{SR} + I_{RR}\right) + \epsilon_s \Phi_{sky} \sigma T_a^4 \left(a + b\sqrt{e}\right) + \epsilon_s \sum_{i=1}^{n} \epsilon_i \Phi_i \sigma T_i^4 - \epsilon_s \sigma T_s^4 + \alpha_c \left(T_a - T_s\right) \quad (1)$$

q : Amount of heat conduction into surface [W/m^2]
T : Temperature [K]
a_{su} : Solar absorptivity
θ : Incidence angle of direct solar radiation [rad]
I_{DR} : Amount of direct solar radiation [W/m^2]
Φ : Shap modulus [sky : sky factor]
I_{SR} : Amount of sky solar radiation [W/m^2]
I_{RR} : Amount of reflected solar radiation [W/m^2]
ε : Longwave emittance
σ : Stefan Boltzmann constant [W/m^{2}K^4]
a,b : Constant on Brunt's formula
e : Water vapor pressure near the ground [Pa]
α_c : Convective heat transfer coefficient [W/m^{2}K]
s(subscript) : Surface
a(subscript) : Atmosphere
n(subscript) : The total number of objects which emit long wave radiation

Convective heat transfer is calculated under the assumption that there is no distribution of air temperature and wind velocity in the subject urban canopy. This approximation is established under the low-wind-velocity condition. The computer performance-based calculation, which excludes CFD, is realized by this approximation. The convective heat transfer coefficient is estimated by the Jurges formula.
One-dimensional heat conduction in each spatial component is simulated, using calculated heat balance data, as the boundary condition for external surface. The boundary conditions for inner side of the surface are the indoor air temperature for the building and the underground temperature for the ground. The backward-difference method is used for the calculation of the unsteady static heat conduction. One running simulation runs for five days in order to obtain a periodic steady-state solution with initial conditions of periodic weather data. The calculation results of surface temperature for the 5th day are used as the output.
This simulation tool evaluates the impact of a proposed building or urban block on the urban thermal environment by two indices based on surface temperature. One index is the Mean Radiant Temperature (MRT) for evaluating the radiative effect on thermal comfort, and the other is the Heat Island Potential (HIP) (Iino A, Hoyano A. 1998), which indicates the total sensible heat from the entire surface of the urban block being analyzed. HIP is expressed as the measure of a temperature, and is calculated by the following Formula (2):

$$HIP = \frac{\int_{AllSurface} \left(T_s - T_a\right) dS}{A} \quad (2)$$

HIP : Heat Island Potential[°C]
T_s : Surface Temperature of each mesh [°C]
T_a : Air Temperature (derived from weather condition data) [°C]
A : Plane area of the urban block[m^2]
dS : Area of each mesh[m^2]

3.4. Post-processing method on the 3D-CAD system

The mesh data of the surface temperature calculation results are converted into surface texture data, and the textures are visually projected onto the 3D-CAD model generated in the pre-process. This allows the user to understand and evaluate the effects of spatial geometry and materials on the outdoor surface temperature from almost any viewpoint, including a bird's-eye view and axonometric projections.

4. Establishment of the simulation parameters and the system

4.1. Optimum mesh size investigation

This subsection describes the results obtained from the mesh size optimization experiments. A small mesh size is necessary in order accurately reproduce detailed spatial components such as eaves, verandas, and the shape of tree crown. On the other hand, a small mesh size significantly increases the calculation load. Therefore, mesh size optimization was conducted.
A building with a small and complex spatial geometry is appropriate for the examination of the mesh dependence, so that a detached house having verandas and eaves was chosen as the building model for the present examination.
The direct solar radiation quantity was calculated for several different mesh size models. Figure 5 shows the relationship between the applied mesh size and the calculation time. The mesh size was varied between 0.1 m and 1.0 m. This figure shows that detailed spatial forms, such as eaves and a wing wall, cannot be sufficiently reproduced when a 1.0 m mesh is applied. The calculation time for the 0.2 m mesh is approximately the same as that for the 0.5 m mesh. Although the 0.1 m mesh results in an accurate reproduction of the building details, the calculation time is long. Therefore, the 0.2 m mesh is suitable

for use in the simulation of subjects having detailed spatial geometry. This size allows for fast simulation while accurately reproducing detailed outdoor spatial geometry.

4.2. Optimum number of tracers in the multi-tracing simulation

The increase in the number of tracers in the multi-tracing simulation used in the estimation of the sky view factor and radiative heat transfer causes the growth of the calculation load, so that the optimum number should be determined for practical use. In this section, we examine the relationship between the number of tracers in the multi-tracing simulation and the calculation accuracy using the sky view factor, which is significant with respect to outdoor heat balance, as the evaluation standard index.

The urban block model used in this examination is an apartment housing area model in a substantial urban area in Tokyo (Fig.6). The Root Mean Square Error (RMSE) index is used for this investigation of calculation accuracy (Formula (3)). The maximum number of tracers for calculating the RMSE, as the standard, is over 63,000.

The relationship between the number of tracers and the RMSE index of the sky view factor for the whole of the ground is shown in Fig. 7. As the number of tracers increases, the value of the RMSE decreases sharply. However the difference in the RMSE is small when using over approximately 500 tracers. When 524 tracers are applied, the RMSE value is less than 1%. The image in Fig. 7 shows the simulation result for the sky view factor distribution on the ground using 524 tracers. A clear distribution of the sky view factor is calculated. This result confirms that for this multi-tracing simulation the suitable number of tracers is more than 500.

5. SIMULATION TOOL APPLICATIONS

5.1. Application to actual urban block

This tool is intended to be applied to architectural design and urban planning at the urban block level. This section describes the application of this tool to actual urban block in Tokyo. Figure 8 depicts the CAD model of the subject urban block, and Fig. 9 depicts the surface temperature calculation results for the urban block.

The calculation time for this subject area, which includes high-rise buildings, was approximately 7 hours using a PC (Macintosh Power Mac G4: 1.25 GHz, Memory: 1 Gbyte). The calculation time for the residential area considered in the next subsection was approximately one hour.

The effect of high-rise buildings on the surface temperature distribution of the surrounding area is clearly illustrated by Fig. 10. This output also shows that the component materials used in the block greatly

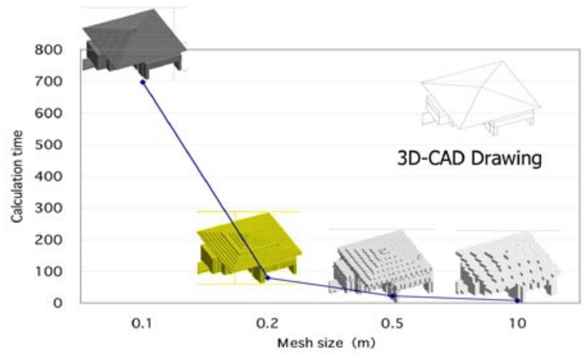


Figure.5 Relationship between the applied mesh size and the calculation time

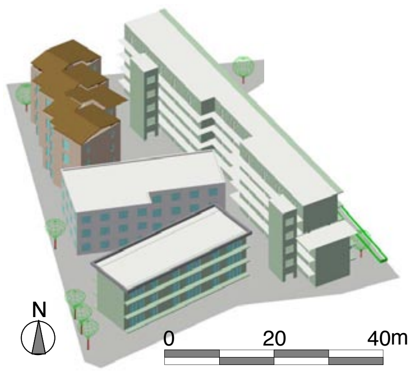


Figure.6 Apartment housing model

$$\mathrm{RMSE} = \sqrt{\frac{\sum_{n=1}^{N} (sf_e - sf_{63180})^2}{N}} \qquad (3)$$

sf_e : Sky view factor using the maximum number of tracer
sf_{63180} : Sky view factor using the each tracer number
N : The number of mesh
RMSE : Calculation error index (Root Mean Square Error)

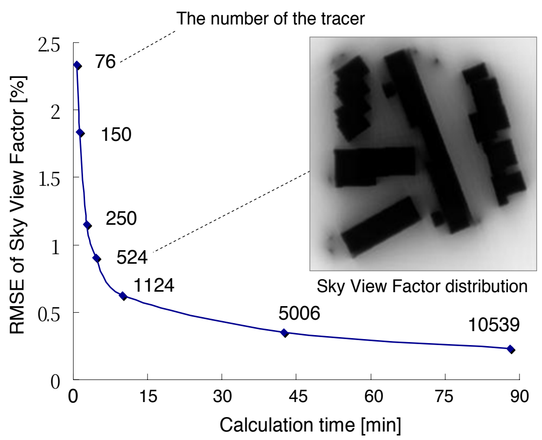


Figure.7 Relationship between the number of tracer and RMSE of Sky View Factor

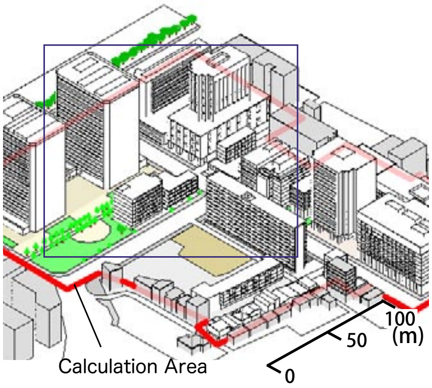
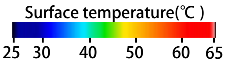


Figure.8 CAD model of the actual uraban blocks for calculation



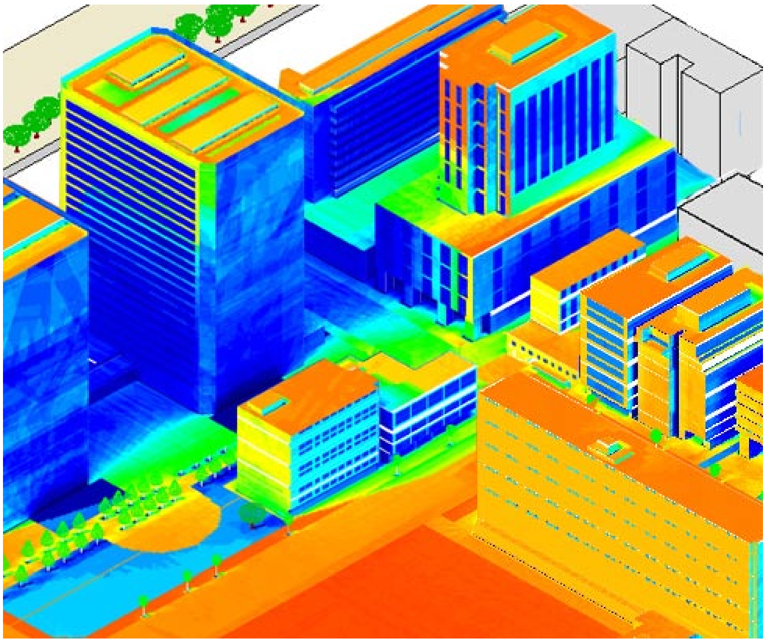


Figure.9 Bird's-eye view of the surface temperature distribution (Clear sky day in summer, 12:00)

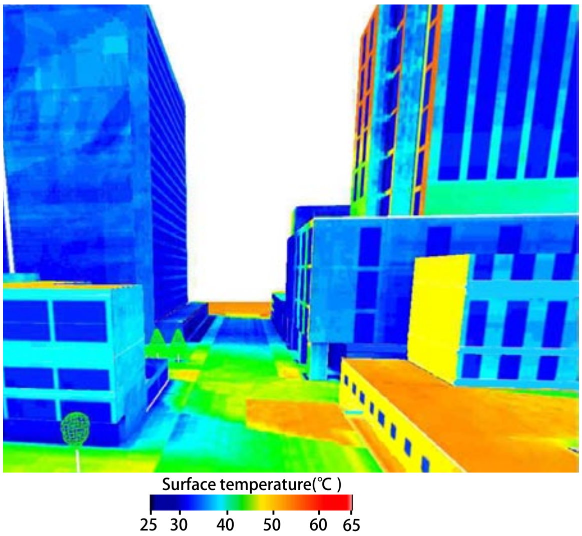


Figure.10 Perspective depiction of the surface temperature distribution(Clear sky day in summer, 12:00)

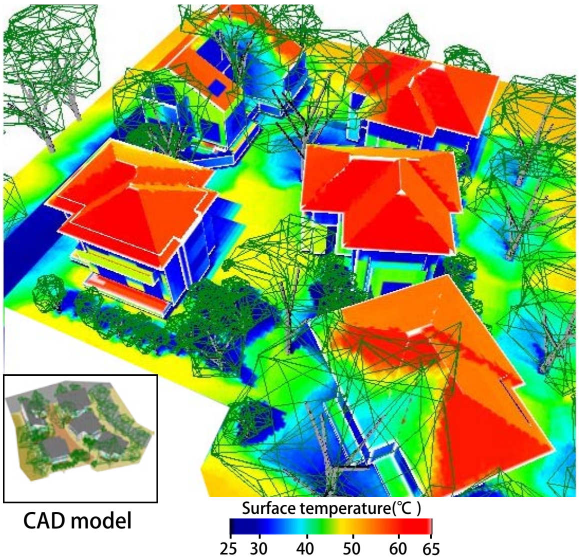


Figure.11 Simulation results of the surface temperature of the residential area (Clear sky day in summer, 12:00)

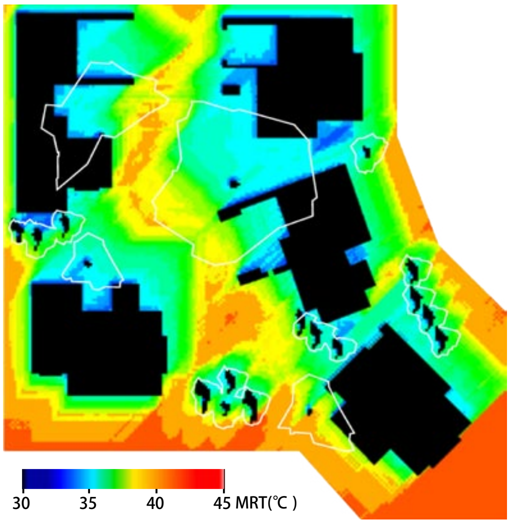


Figure.12 MRT distribution at a height of 1.5m (Clear sky day in summer, 12:00)

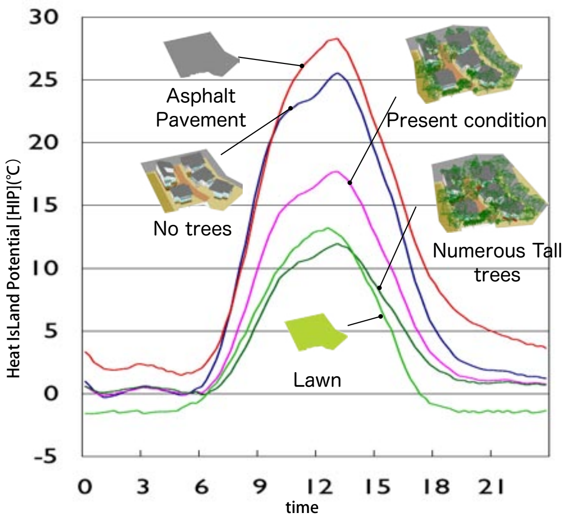


Figure.13 Diurnal variation of HIP

affect the surface temperature distribution.

5.2. Application to the evaluation of the effect of planting tall trees

In order to confirm the applicability of this simulation tool for the purpose of thermal design of outdoor spaces, this tool was applied to an area containing detached houses surrounded by numerous trees with leafy canopies.

Figures 11 shows a bird's-eye view of the surface temperature distribution depicted in the 3D-CAD model, as well as a perspective depiction of surface temperature distributions. The effect of shade from the tall trees results in numerous surfaces having temperatures that are approximately equivalent to the ambient air temperature.

Figure 12 depicts the MRT distribution at a height of 1.5 m. The MRT under the tall trees is 32°C, which is approximately 10°C lower than that observed in areas exposed to a solar radiation.

Figure 13 shows the diurnal variation of the HIP. The calculation was performed for three different scenarios, which differ with respect to the number and position of trees. This figure indicates that the HIP drops markedly due to the presence of tall trees.

These results reveal that the tool is able to simulate the effects of building shapes, materials and trees shade on the surface temperature distribution, and the MRT and HIP indexes. Therefore, this simulation tool has been demonstrated to be useful in evaluating the impact of a proposed design on the urban thermal environment by using the results of surface temperature.

6. CONCLUSION

This paper details the development of a simulation tool that will enable the user to virtually predict and evaluate the effect of building and urban block designs on the thermal environment of an area using a 3D-CAD software. In order to allow for prediction taking into account detailed outdoor spatial geometry and to allow the system to be put into practical use, the following features were examined and incorporated into this simulation tool: the input and pre-processing method using the CAD system and the GUI, the database linking the design parameters and the parameters for the heat transfer calculation, the simulation algorithm is improved to further reduce the calculation time and PC memory required for the simulation, allowing the system to be run on a personal computer, Establishment of the simulation parameters and the system and a method for visually expressing the results of the calculations via 3D-CAD.

The results of the application of this simulation tool in an area of detached houses confirms that the simulation tool is able to simulate the effects of spatial geometry and materials existing in the outdoor space, including the effect of shading by tall trees, on the surface temperatures and evaluation indexes of urban thermal environments.

The examination using a broader range of examples of urban areas will be conducted in a future study. Future research will focus on the introduction of a latent heat calculation model to evaluate the influence of rainfall and evaporative cooling. In addition, this system will be combined with CFD in order to predict the air flow and air temperature distribution in an area.

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REFERENCES

Bruse M, Fleer H. 1998. "Simulating surface-plant-air interactions inside urban environments with a three dimensional numerical model". Environmental Modelling & Software 1998; 13: 373-384

Anonymity. ENVI-met web homepage, http://envi-met.com/

Iino A, Hoyano A. 1998. "Development of a method to predict the heat island potential using remote sensing and GIS data". Energy and Building 1996; 23: 199-205