Radiative heat transfer simulation between outdoor and indoor spaces for predicting the performance of a direct heat gain system

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ABSTRACT

A direct heat gain system, which is an example of a passive system using solar heat, is employed in some buildings in Japan. In order to design a direct heat gain system, it is important to consider the outdoor environment, such as surrounding buildings and trees. In addition, if a building is affected by the outdoor environment, indoor factors such as the position of heat storage materials and windows can be taken into account when designing a direct heat gain system.

This study presents a simulation of radiative heat transfer between outdoor and indoor environments for predicting the performance of a direct heat gain system. The solar radiation received by external building surfaces is calculated by ray tracing method, and the solar radiation on the internal surfaces is calculated by taking into account the material and position of the heat storage material and the direction of solar radiation. The calculated solar radiation values are entered into the multiroom heat load simulation to calculate the room air temperature.

In this study, the calculation accuracy of room air temperature depends on reproducibility of building geometry in the numerical simulation. This study confirms the effectiveness of the presented simulation model by analysing the influence of these error factors on the calculation accuracy of room air temperature. Finally, this study analyses the influence of outdoor environment and indoor factor on the performance of the direct heat gain system as a case study. The results show that the calculated room air temperature is affected by the solar heat gains, which depend on the outdoor condition, and that the room air temperature fluctuates in response to the position of the heat storage material and window.

KEYWORDS

Outdoor thermal radiation environment, Direct heat gain system, Numerical simulation, Building heat load

INTRODUCTION

A direct heat gain system is an example of passive systems. However, their performance in actual buildings is affected by the outdoor environment, including trees and surrounding buildings. In addition, if a building is affected by the outdoor environment, indoor factors such as the position of heat storage materials and windows can be taken into account when designing direct heat gain systems (Fig. 1). This relationship between the outdoor environment and the design of heat storage materials and windows affects the total solar radiation, which in turn influences room air temperature.

This study presents a simulation of heat transfer between outdoor and indoor environments for predicting the performance of direct heat gain systems. In addition, the effects of the outdoor environment on the performance of direct heat gain systems are evaluated by the presented simulation for each different indoor model.

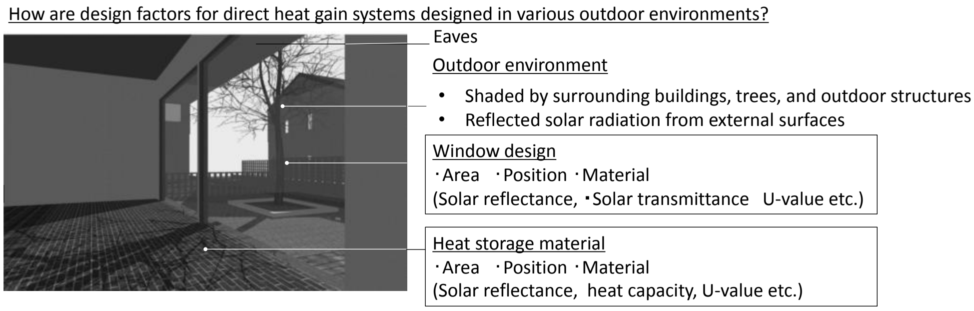

Figure 1. *Design factors for direct heat gain systems*

PROBLEMS IN PREDICTING PERFORMANCE OF DIRECT HEAT GAIN SYSTEMS

The literature mentions several simulation methods for predicting room air temperature and heat load. Most of these methods (Sakamoto et al. 1988, Ozaki et al. 2004, Kodama et al. 1987) calculate the solar radiation on external surfaces by using simple parameters such as the pitch of a building and the height of adjacent buildings (Table 1). In these studies, the solar radiation transmitted into rooms is assumed to be distributed across internal surfaces regardless of the position of heat storage materials and the direction of solar radiation.

We perform the following steps to predict the performance of buildings with direct heat gain systems:

- The total solar radiation on external surfaces is calculated using a method that takes into account the outdoor thermal radiation environment.
- In the heat load simulation, the total solar radiation incident on internal surfaces is calculated using a method that takes into account the material and position of the heat storage material and the direction of solar radiation.

Table 1. *Previous methods for predicting room air temperature and building heat load*

Previous method	Solar radiation incident on external surfaces	Solar radiation transmitted into the indoor space
Sakamoto（1988）（SMASH）	Considering the shading effect by simple parameter : pitch of buildings, height of buildings	Transmitted solar radiation is distributed among internal surfaces on the basis of the parameter that depends on the area of each surface(without considering the direction of solar radiation)
Ozaki（2004）（THERB）	Considering the shading effect of eaves, side walls	Considering the multiple reflection on the internal surfaces(Gebhart's absorption methods)
Kodama,Takemasa (1987)（PASSWORK）	Assumption of the shading effect by multiplying the coefficient	Direct solar radiation: distributed to the floor and wall by the projected area of direct solar radiation on the floor Sky solar radiation: distributed to the floor, wall and ceiling by the parameter depending on the area of each surface
Asawa (2008)（3D CAD-based thermal environment simulator）	The three dimensional spatial form of the outdoor environment is divided into voxel meshes and the outdoor thermal balance equation is solved for each voxel	Same as Sakamoto's method

MODEL FOR ANALYZING RADIATIVE HEAT TRANSFER BETWEEN OUTDOOR AND INDOOR SPACES

This paper proposes a simulation of heat transfer between outdoor and indoor spaces to predict the effects of the relationship between the outdoor environment and indoor factors on the performance of direct heat gain systems. The simulation is outlined in Fig. 2. The simulation calculates the total solar radiation incident on internal surfaces on the basis of previous method (He et al. 2008), and the calculated radiation is used as an internal boundary condition for heat load simulation.

Calculation of total solar radiation on external surfaces

This study calculates the total radiation on external surfaces on the basis of Asawa's method (2009). In this method, three-dimensional spatial forms of buildings, trees, and other structures, as well as two-dimensional ground surfaces are divided into voxel meshes (mesh size: 200 mm). For each mesh, the direct solar radiation, sky solar radiation, reflected solar radiation, atmospheric radiation, and long-wave radiation from surrounding buildings are simulated (Fig. 2). The unsteady one-dimensional heat balance equation is then solved using these parameters for each mesh, and external surface temperature is simulated.

Calculation of total solar radiation on internal surfaces

The total solar radiation on internal surfaces is simulated by a ray tracing method and Gebhart's absorption method. In this simulation, first, the spatial forms of the wall, floor, window, and ceiling are divided into voxel meshes (mesh size: 200 mm). Finally, the total solar radiation is calculated by summing the direct solar radiation, sky solar radiation, and reflected solar radiation.

Next, a ray traces the direction of direct solar radiation from each mesh of the wall, floor, window, and ceiling, and then, the direct solar radiation incident on internal surfaces is simulated. Direct solar radiation is the simulated quantity multiplied by the solar transmittance of the window; the angle of direct solar radiation is taken into consideration in this simulation.

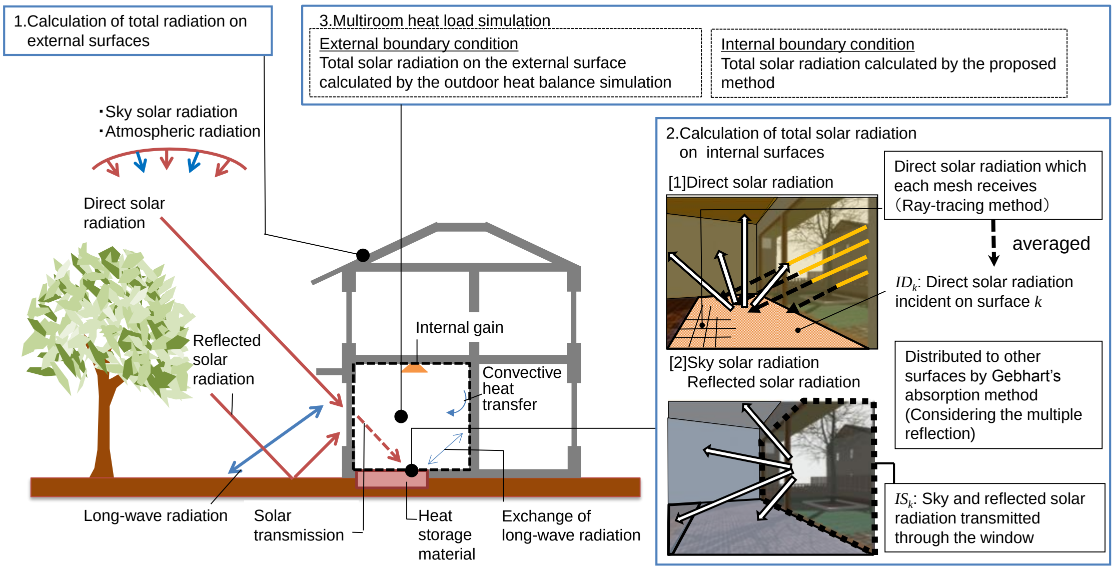

Figure 2. *Outline of proposed simulation tool for predicting the performance of direct heat gain systems*

$$JD_j = (1-\rho_j)ID_j + \sum_{k=1}^{N} R_{kj}\rho_k ID_k \tag{1}$$

$$R_{ij} = (1-\rho_j)F_{ij} + \sum_{k=1}^{N} F_{ik}\rho_k R_{kj} \tag{2}$$

$$JS_j = \sum_{k=1}^{N} R_{kj} IS_k \tag{3}$$

Here R_{ij} is solar absorption by an internal surface j in internal surface i, F_{ij} is the view factor from the internal surface i to j, ρ_j is solar reflectance of the internal surface j, ID_k is direct solar radiation incident on the surface i [W/m^2], JD_j is direct solar radiation absorbed on the internal surface j [W/m^2], Is_k is the sum of sky and reflected solar radiations transmitted through the window i [W/m^2], JS_j is the sum of the sky and reflected solar radiations absorbed on the internal surface j [W/m^2], and J_j is the total solar radiation absorbed on the internal surface j [W/m^2]

The calculated direct solar radiation for each mesh is averaged for each surface. The averaged direct solar radiation incident on each surface is mutually distributed among the other surfaces according to Gebhart's absorption method (Gebhart 1959) [Eqs. (1), (2)]. The sky solar radiation and reflected solar radiation calculated by the outdoor thermal balance simulation in the voxel meshes of the window are averaged for each window surface, and then, the sky and reflected solar radiations incident on internal surfaces are simulated according to Gebhart's absorption method [Eq. (3)].

Multiroom heat load simulation

The building heat load is calculated by entering the external and internal boundary conditions as input. The external boundary condition is the total solar radiation on external surfaces and includes direct solar radiation, sky solar radiation, reflected solar radiation, atmospheric radiation, and exchange of long-wave radiation with the surroundings. The internal boundary condition is calculated by the proposed method. This simulation can calculate room air temperature and heat load using the multiroom model.

EFFECT OF REPRODUCIBILITY IN THE PROPOSED SIMULATION ON CALCULATION RESULTS

Building model and weather conditions

In the proposed simulation, the mesh size in the outdoor thermal environment simulation can be a source of error. This study analyses the effect of this error on the calculation results. Fig 3(Analysis1) shows the analysis patterns. In this analysis, standard model N-S is compared with models N-1 to N-4. These models differ in the size of the window, eaves, and fence. For example, the N-1 model assumes that the window width estimated in the mesh generation process is 0.2 m less than the real width.

The wooden house model proposed by the Architectural Institute of Japan (1985) is used as the building model for the analysis. This model includes a large window and eaves. Weather data for a sunny winter day in January23 in Tokyo are used as the weather conditions for this analysis.

Simulation results

Table 2 presents the effects of the error cause on the calculation results. The difference in room air temperature caused by the reproducibility error of building geometry is less than 1.6°C. This difference is seen when comparing two models that differ in the height of the fence (N-3 and N-4).

Existing methods do not account for the position of the heat storage material and the direction of solar radiation. For this reason, the amount of solar radiation absorbed in the heat storage material is underestimated. In our simulation results for the N-S model, the fluctuation of room air temperature is 2.3°C larger than that for existing methods.

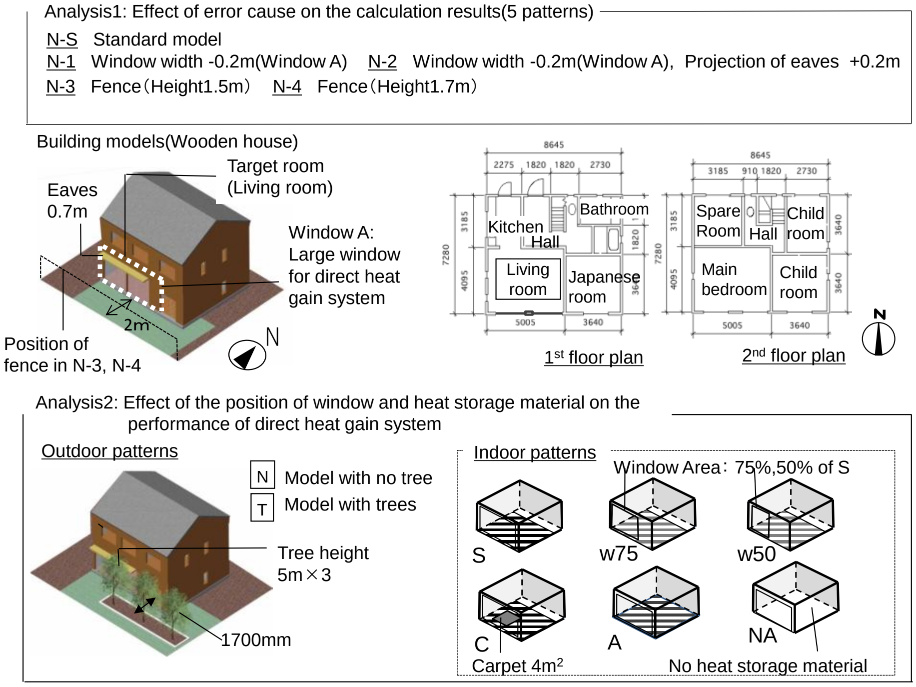

***Figure 3.** Analysis patterns*

***Table 2.** Effects of error cause on the calculation results*

	Difference of total solar radiation on the heat storage material[W](Max.)	Difference of room air temperature [℃]（Max.）
Difference in width of window <N-1>-<N-S>	-190W (10:30）	-0.5℃ (10:45）
Difference in projection of eaves <N-2>-<N-1>	-350W (12:45）	-1.0℃ (14:30）
Difference in height of fence <N-4>-<N-3>	-370W (12:45）	-1.6℃ (15:30）

EFFECT OF TREES IN OUTDOOR SPACE ON PERFORMANCE OF DIRECT HEAT GAIN SYSTEM

Analysis Models

The analysis involved 12 models with different combinations of tree patterns, window position and area, and heat storage materials (Fig. 3, Anlaysis2). The variation in tree patterns is represented by “T” and “N.” T has three trees of height 5 m each, and N includes no trees; the trees are located south of the buildings.

Variations in indoor design are shown in Fig. 3 (S, w75, w50, C, A, NA). The six patterns differ in the position and area of windows and heat storage materials in the living room. Analysis models are represented as T-S in this paper.

Effect of window position on room air temperature

Fig. 5 shows the total solar radiation absorbed daily in the heat storage material and the daily fluctuation in room air temperature in each case. In models with small windows, such as N-w50, the maximum room air temperature is up to 4 °C lower than that in N-S and the minimum room air temperature is equivalent to that in N-S.

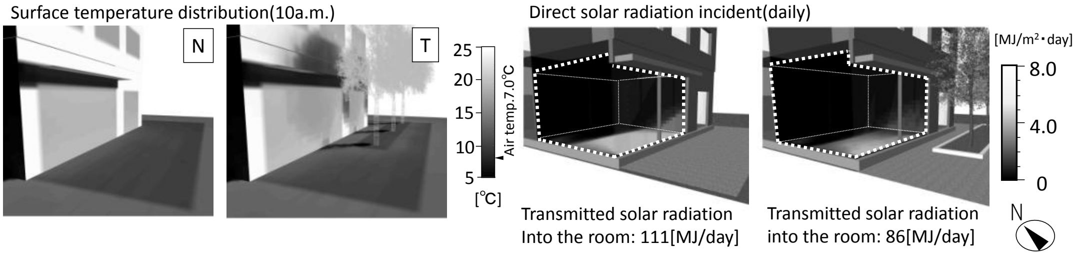

Figure 4. *Distribution of surface temperature (10 a.m.) and incident daily direct solar radiation*

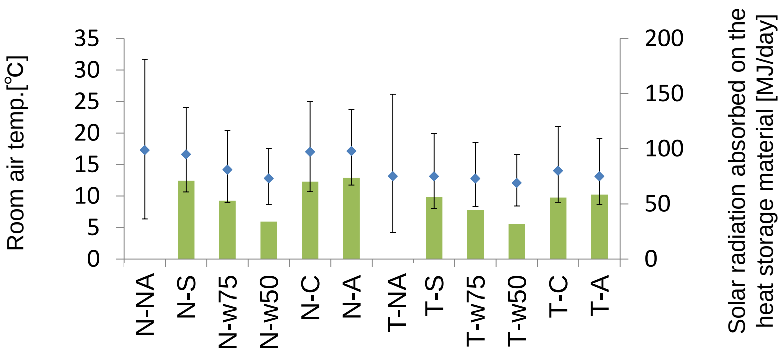

Figure 5. *Daily fluctuation in room air temperature and solar radiation absorbed on the heat storage material*

If the building is in the shadow of a tree, as in T, the total solar radiation absorbed in the heat storage material is 23% less than that in N-S and the average room air temperature is 3.5°C less than that in N-S.

The heat storage material raises the minimum room air temperature, although the room does not gain solar radiation enough like T. The minimum room air temperature in T-S, w75, and w50 is 3.7–4.3°C higher than that in T-NA, which has no heat storage material.

When the heat loss is suppressed by the small window under the condition that the building is affected by the shadow of a tree as in T-w50, the effect on the room air temperature in the night is minimal. The minimum room air temperature in T-S and T-w50 is similar. On the other hand, the maximum room air temperature shows a difference of 3.3°C between T-S and T-w50.

Effect of position of heat storage material on room air temperature

In N-S as standard model, the amount of solar radiation absorbed in the heat storage material is similar to that in N-A, which has heat storage on every floor. For this reason, the difference in room air temperature fluctuation between two cases is within 1°C (Fig. 5). The same applies to a comparison of T-S and T-A.

If the heat storage material is covered with a carpet (thickness: 6 mm), the heat storage performance is poorer owing to the heat insulating effect of the carpet. The fluctuation range of room air temperature in T-C is 1°C higher than that in T-S.

CONCLUSION

This paper proposed a heat transfer model between outdoor and indoor spaces for predicting the performance of direct heat gain systems. The analysis results led to the following conclusions:

- To show the effectiveness of proposed simulation method, the effect of reproducibility of building geometry on the simulation result is confirmed.
- We determined that the difference in the position of trees causes a difference of up to 3.5°C in the average room air temperature and that heat storage by a storage material affects the room air temperature in the night, even when the room does not receive enough solar radiation in the daytime.
- The position of the heat storage material and carpet affects the total solar radiation absorbed in the heat storage material in each outdoor environment.

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REFERENCES

Y. Sakamoto. 1988. Development of calculation program for heating and cooling energy SMASH, *IBEC*. 49: 25-29 (In Japanese)

A. Ozaki. 2004. Combined simulation of heat and air and moisture on the hygrothermal environment and heating /cooling load, *Annual convention of AIJ*. 2004: 216-219 (In Japanese)

Y. Kodama and K. Takemasa. 1987. A practical method with personal computer to predict thermal performance of passive solar design, *J. Environ. Eng. AIJ.* 374: 44-53 (In Japanese)

T. Asawa, A. Hoyano, and K. Nakaohkubo. 2008. Thermal design tool for outdoor spaces based on heat balance simulation using a 3DCAD system, *Building and Environment.* 43: 2112-2123

H. Jiang, A. Hoyano, and T. Asawa. 2009. A numerical simulation tool for predicting the impact of outdoor thermal environment on building energy performance, *Applied Energy* 86: 1596-1605

B. Gebhart. 1959. A new method for calculating radiant exchanges, *ASHRAE Transactions*. 65:

Architectural Institute of Japan. 1985. The present situation and the problems of the heat-transfer analysis, *The Text of the 15th AIJ Symposium on Heat*: 23-33 (In Japanese)